Sustainable Production, Life Cycle Engineering and Management

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EcoDesign and Sustainability II

Social Perspectives and Sustainability Assessment

Springer

Sustainable Production, Life Cycle Engineering and Management

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Preface

EcoDesign has been a core concept for the manufacturing industry in its efforts to transform the mass production, mass consumption, and mass disposal paradigm toward achieving sustainability. In the last two decades, the ecosystem of the manufacturing industry has been rapidly changing, especially when we look at Sustainable Development Goals (SDGs), circular economy, and digitalization. In addition, the COVID-19 pandemic has drastically changed our lifestyles to the "New Normal," where a typical example is to shift from working in the office to working from home using a teleconference system. In response to such emerging needs and enablers, though the impact of COVID-19 has not yet been considered, the scope of EcoDesign has been expanding to cover more diversified areas, such as environmentally conscious design of products, services, manufacturing systems, supply chain, consumption, economies, and society.

This book collates 79 papers out of 205 papers presented at EcoDesign 2019—the 11th International Symposium on Environmentally Conscious Design and Inverse Manufacturing, which was held in Yokohama, Japan, from November 25 to 27, 2019. All the 79 papers were peer-reviewed by the EcoDesign 2019 Executive committee. Celebrating the 20 years anniversary of the symposium since its first occurrence in 1999, EcoDesign 2019 provided the excellent platform to share state-of-the-art research and practices in the field of EcoDesign. The total of 278 researchers and practitioners from 28 countries participated in EcoDesign 2019.

The book consists of two volumes, i.e., the first volume focuses on "Products, Services, and Business Models," and the second volume focuses on "Social Perspectives and Sustainability Assessment." Reflecting the expansion of the symposium scope, the book chapters cover broad areas—product and service design, business models and policies, circular production and life cycle management, green technologies, sustainable manufacturing, sustainable design and user behavior, sustainable consumption and production, EcoDesign of social infrastructure, sustainability education, sustainability assessment and indicators, and energy system design. We believe that the methods, tools, and practices described in the chapters are useful for readers to facilitate value creation for sustainability.

Last but not least, we would like to express our sincere appreciation to all the contributors, supporters, and participants of EcoDesign 2019. This book cannot be published without the help of the executive committee members who cooperated in the peer review of the papers.

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Contents

Part I
Sustainable Design and User Behavior

Chapter 1
The Chinese-Brand Electric Vehicles in the Eyes of the US Consumers

Kenichiro Chinen, Hideki Endo, Mitsutaka Matsumoto, and Yongliang Stanley Han

Abstract Researchers have found how driving electric vehicles (EVs) can be one solution to the negative environmental impact of petrol or diesel cars because they produce substantially lower emissions and are more energy-efficient than conventional cars. EVs are predicted to be the disruptive market force for transportation and technology. Of one million EVs sold in 2017, more than half of global sales were in China. China has a strong leadership position in the EV industry. The purpose of this study is to examine the US consumers' reliance on Country-Of-Origin (COO) information in evaluating the quality of the Chinese-brand EVs (CBEVs) made-in various countries. Researchers suggest that consumers use COO as an information cue when evaluating a product, particularly if they lack detailed knowledge of the product. The results show that the perceived product quality of electric vehicles made in various countries influences consumers' purchasing behavior. The study also found that consumers' ethnocentrism has an effect on their buying behavior.

Keywords Electric vehicles · Chinese-brand · Country-Of-Origin · Ethnocentric

1.1 Introduction

Researchers have found how driving an electric vehicle (EV) can produce substantially lower emissions than a petrol or diesel car. According to the International Energy Agency, the total number of EVs in the global market surpassed three million in 2017. Of one million EVs sold in 2017, more than half of global sales were in China. China has a strong leadership position in the EV industry (Perkowski 2018). However,

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"Chinese EVs are still several years behind the global leaders in terms of technologies" (Schmidt 2018). The purpose of this study is to examine the US consumers' reliance on Country-Of-Origin (COO) information in evaluating the quality of the Chinese-brand EVs (CBEVs) made-in various countries.

China contributes to approximately 65% of the US trade deficits in 2017. This trade imbalance led to the US-China trade war in 2018. Therefore, the attitudes and opinions of the US consumers towards China and its products, directly and indirectly, may influence demand for products of Chinese-brand products or products made in China. The US President Trump's campaign in tweeting and preaching China's unfair policies does not help improve China's country image. It is very important for China to know its product image in foreign markets, particularly in the US. This research is timely because Chinese companies are reported to open stores focusing on sales of EVs in the US market as early as 2019. Despite the length of exposure to "Made-in China" products and significant demand observed for Chinese products in the US market, previous studies show that the image of "Made-in China" is stereotyped.

The outline of this paper is as follows. First, we state the theoretical background and research questions. Second, we examine the methodology used to conduct our investigation. Third, we present the results of the data analysis and hypotheses testing. Fourth, we summarize the research findings and discuss both practical implications. In the last section, we conclude and investigate possible avenues for future research.

1.2 Literature Review

Past studies find that COO provides an important informational cue in consumers' evaluations of products and have empirically demonstrated country equity in their studies (Heslop and Papadopoulos 1993). With the increasing economic interdependence of national economies across the world, production occurs sequentially across multiple countries. Multiple countries of origin may have confused consumers in identifying the actual origin of the product. Jaffe and Nebenzahl (2006) state that "companies often ignore the country image effect altogether, treating the world as a single market and source of products" (Jaffe and Nebenzahl 2006). They warn the tendency of making sourcing decisions "based on comparative advantage and cost differentials only, to the exclusion of image considerations" (Jaffe and Nebenzahl 2006).

1.2.1 Product Quality, Perceived Benefits, and Perceived Risks

Cross-national studies of the perceptions of "Made in" images are important because of their managerial implications for global and multinational companies. International marketers, marketing scholars, economists, and politicians understand that image of a country where a product is made is essential because the COO of a product influences product evaluations and purchase decisions; consumers tend to infer the quality of a country's products from its national image (Heslop and Papadopoulos 1993). We formulate the following hypothesis:

H1a: Perceived product quality positively influence the purchase intention of the CBEVs.

In general, people are aware of damage to the environment and going green is a social norm. The electrification, or powered by electricity, will lead to a significant amount of reduction in greenhouse gas emissions and a decreased dependence on crude oil (Barbarossa et al. 2015). The EVs offer an advantage to reduce greenhouse gas emissions, air pollution, and vehicular noise. We establish the following hypothesis:

H1b: Perceived benefits positively influence the purchase intention of the CBEVs.

In general, researchers find that high perceived risk and low perceived quality of green products are both negatively associated with consumers' purchasing behavior (Matsumoto et al. 2018). Morton et al. (2016) examine environmental concerns and report how consequences of car use, self-reported responsibility and willingness to pay to reduce emissions are associated with attitudes towards EVs (Morton et al. 2016). People who consider their cars to be in their everyday life may have negative attitudes towards EVs (Morton et al. 2016). People still see risks and concerns about EVs regard a limited driving distance, time required to recharge, and a limited number of charging stations. Therefore, we have set forth the following hypothesis:

H1c: Perceived risks negatively influence the purchase intention of the CBEVs.

1.2.2 China's Economic Success

In 2015, the Chinese government launched "Made in China 2025", a state-led strategic industrial policy that seeks to make China dominant in global high-tech manufacturing, including, but not limited to, electric and new energy (e.g., hydrogen-fuel cell) vehicles as well as artificial intelligence. For the US, the China's industrial policy "undermine[s] Beijing's stated adherence… to international trade rules, leading President Donald J. Trump to levy tariffs on Chinese goods and block several Chinese-backed acquisitions of technology firms" (McBride 2018). Regarding China's trade practices, Trump has been tweeting and preaching his 'fair' business doctrine, particularly to his US supporters:

> If the U.S. sells a car into China, there is a tax of 25%… The days of the U.S. being ripped-off by other nations is OVER! (Sept 9, 2018)

> … I am a Tariff Man. When people or countries come into raid the great wealth of our Nation, I want them to pay for the privilege of doing so…MAKE AMERICA RICH AGAIN (Dec 4, 2018).

The COO image inaugurates US consumer's beliefs and perceptions about attributes of EVs, and in turn, these beliefs affect their attitudes and inferences about product quality towards the CBEVs. Therefore, we formulated the following hypotheses:

H2a: In evaluating the CBEVs made in China and advanced countries, the high-ethnocentric US consumers are likely to perceive the product quality made in foreign countries to be inferior to those who are low-ethnocentric consumers.
H2b: The low-ethnocentric US consumers are willing to purchase the CBEVs made in China and advanced countries than those who are high-ethnocentric consumers.

1.3 Methodology

1.3.1 Respondents

The online and paper-and-pencil surveys were anonymous and self-administered. We ensured confidentiality and promoted confidence in providing sensitive information accurately. No personal information was sufficient to identify any participants. A total of 188 business students from a major university in Sacramento, California, completed surveys. Ten observations from the 188 respondents had to be removed because of missing information. It is important to acknowledge that the survey sample was not randomly selected. Research indicates that paper-and-pencil and Internet data collection methods generally produce equivalent results (Weigold et al. 2013). Moreover, anonymous online surveys have the advantage to yield significantly lower social desirability scores than non-anonymous or face-to-face surveys (Dodou and de Winter 2014). The topic of the survey was announced as a survey on "opinions of consumers on electric vehicles" without explicitly referring to sustainability issues.

1.3.2 Key Variables

1.3.2.1 Purchase Intention and Product Quality

According to Wang et al. (2013), purchase intention toward CBEVs (*PI*) is defined as "individual assessment of future willing to buy". Our survey checks *PI* by the following Likert scale question:

- I am willing to purchase a CBEVs, labeled as "Made in (*country*)".

The scale ranges from "1: strongly disagree" to "5: strongly agree".

Perceived product quality toward CBEVs consists of four questions with the five-point Likert scale about technological advancement, workmanship, reliability, and safety modified from Klein (2002). For example on safety,

- I think Chinese-brand EV, labeled as "Made in [*country*]" is safe to drive.

The score of perceived product quality (*PQ*) is derived from the average of the scores of these four aspects.

1.3.2.2 Perceptions Toward CBEVs

The questionnaire items measuring the respondents' perceptions toward CBEVs are modified from Wang et al. (2013) and Matsumoto et al. (2018). Perceived benefits index (*PB*) is constructed by two items:

- Buying EV instead of a conventional car can lead to resource and energy savings
- Buying EV instead of a conventional car can reduce the harmful effect on the environment.

Perceived risks index (*PR*) is three items

- The quality and the safety of EV is not as good as that of a conventional car
- The EV does not perform and function as well as a conventional car
- Buying EV is not a good investment.

The scores of five items are measured by the above-mentioned scale. *PB* and *PR* are calculated by the average of scores of items within each construct.

1.3.2.3 Ethnocentrism

A respondent's ethnocentrism index (*ET*) is measured by four questionnaire items modified from Klein (2002):

- It is not right to purchase foreign cars because it puts Americans out of a job
- A real American should always buy American automobiles
- Americans should not buy foreign products, because this hurts American business and causes unemployment
- We should purchase automobiles made in the USA instead of letting other countries get rich off of us.

This combination takes care of the multicollinearity issue. All four items are measured by the five-point scale as before. *ET* is derived from the average of the scores of four items. We transform this variable from continuous to dichotomous by separating $ET > 3$ (high levels) from $ET \leq 3$ (not high levels).

1.3.3 Statistical Analysis

1.3.3.1 Hypotheses H1a, b, c

We accept the ordinal response model to examine the influence of a respondent's quality image toward CBEVs made in country c (PQ_c), perceived benefits of buying EVs (PB), and perceived risks toward EVs on his/her purchase intention toward country c's CBEVs (PI_c). "c" includes China, the US, Sweden, Mexico, South Korea, and Japan.

We define a latent variable PI_c^* and set the structural model as $PI_{ci}^* = \boldsymbol{S}_i\boldsymbol{\beta} + \gamma PQ_{ci} + \theta PB_i + \tau PR_i + e_i$. The subscript i denotes ith respondent, and $\boldsymbol{S}_i$ is the vector of ith respondent's personal characteristics adopted as the control variable: gender (female = 1), traditional college-age (18–24 years old = 1), ethnicity (White = 1), and political support (Republicans = 1). e_i is the error term. Our interest is that the signs of γ, θ, and τ support the hypotheses H1a, H1b, and H1c.

We ask the respondents for their willingness to purchase a CBEV made in country c by a five-point Likert scale ranging from "1: strongly disagree" to "5: strongly agree", because we are not able to observe PI_c^* directly. The number of the sample size is limited. "Strongly (dis)agree" and "(dis)agree" are integrated into the same category, because we could not perform some regressions and statistical tests under each dependent variable PI_c consists of five categories. Thus, PI_c is reclassified into the following three categories,

$$PI_c = \begin{cases} 1: \text{(strongly) disagree,} & \text{if } -\infty < PI_{ci}^* \le t_1 \\ 2: \text{neutral,} & \text{if } t_1 < PI_{ci}^* \le t_2 \\ 3: \text{(strongly) agree,} & \text{if } t_2 < PI_{ci}^* \le \infty. \end{cases}$$

$t_\nu (\nu = 1, 2)$ is a threshold between adjacent two options of the response variable PI_c. Thus, the ordered logit model is appropriate for analyzing the influence of selected independent variables on changes in the response variable PI_c. Hereafter, $PI_c = 1$ denotes 'disagree' and $PI_c = 3$ is 'agree'.

1.3.3.2 Hypotheses H2a, b

Our interest is whether respondents' ethnocentrism has negative influences on their perceived product qualities toward CBEVs made in target countries and their purchase intentions toward them or not. The error terms between two structural models with latent dependent variable PQ_c^* and PI_c^* may be correlated under the hypothesis H1a is supported. Thus, the bivariate probit model is applied to handle this problem. Because the bivariate probit model requests a dichotomous response variable, we redefine these variables as follows:

$$PQ_c^H = \begin{cases} 0(\text{not high product quality}), & \text{if } PQ_c \le 3 \\ 1(\text{high product quality}), & \text{if } PQ_c > 3, \end{cases}$$

$$PI_c^A = \begin{cases} 0(\text{not agree}), & \text{if } PI_c = 1, 2 \\ 1(\text{agree}), & \text{if } PI_c = 3. \end{cases}$$

1.4 Results

1.4.1 Summary Statistics

1.4.1.1 Purchase Intention and Product Quality

Table 1.1 shows the respondents who are willing to purchase Chinese CBEVs (PQ_{China}) are 41.0% of them and those who have low purchase intention are 21.9%. ‘Agree’ of PI_{US} is the highest proportion (52.5%) and that of PI_{Mexico} is the lowest (18.6%). In the same manner, perceived product quality in the US (PQ_{US}) is the highest score (3.559) and PQ_{Mexico} is the lowest (2.596). PQ_{US}^H (the proportion of $PQ_{US} > 3$) is 62.9%, the highest among six countries.

1.4.1.2 Perceptions Toward CBEVs

The mean and the standard deviation of *PB* is 3.689 and 0.960 (N = 175). The mean and the standard deviation of *PR* are 2.605 and 0.854 (N = 178). Since the Cronbach’s *alpha* statistic for *PB* and *PR* is higher than 0.75, it is considered that the elements in *PB* and *PR* have internal consistency.

Table 1.1 Purchase intention and perceived product quality toward CBEVs

		CH	US	SW	MX	KR	JP
PIc	Disagree	0.22	0.12	0.23	0.42	0.20	0.12
	Neutral	0.37	0.35	0.54	0.40	0.50	0.39
	Agree	0.41	0.53	0.24	0.19	0.31	0.49
PQc	Score	3.01	3.56	3.07	2.60	3.02	3.51
	Proportion of $PQ_c > 3$	0.34	0.63	0.35	0.16	0.35	0.59
N		178	177	177	177	177	176

Note CH: China; US: USA; SW: Sweden; MX: Mexico; KR: South Korea; JP: Japan

1.4.1.3 Ethnocentrism and Control Variables

The high level of ethnocentrism ($ET > 3$) is 16.9% of the respondents (N = 178). The proportion of females is 41.7% (N = 175). Traditional college-age respondents represent 75.1% of 177 respondents and White respondents are 38.8% of 165 respondents. Respondents who supported Republicans are 43.5% (N = 170).

1.4.1.4 Hypotheses H1a, b, c

The ordered logit model requires a test of parallel regression assumption that all slope coefficients are statistically identical. We verify them by Wolfe-Gould test under the null hypothesis is $\gamma_1 = \gamma_2$. If the test does not reject the null hypothesis, we accept the ordered logit model under $\gamma_1 = \gamma_2$ (the constrained model). The significance probabilities of all countries are more than 0.15, therefore we accept the constrained model.

The results in Table 1.2 indicate all countries' PQ_cs have significant influences on PI_cs. The factor change in the odds for a unit increase in PQ_c is derived by $\exp(\hat{\gamma})$. For example, $\hat{\gamma}_{China}$ is 1.776 and $\exp(\hat{\gamma}_{China}) = 5.905$. The odds of the outcome 'agree (neutral)' toward CBEVs made in China are 5.905 times larger than the outcome 'neutral (disagree)'. These results support the hypothesis H1a.

Most of the estimates of *PB* and *PR* are insignificant. These results indicate that perceived benefits of buying EVs and perceived risks toward them do not have significant influences on his/her purchase intention toward each country's CBEVs except the effect of perceived benefit on Chinese CBEVs. The hypotheses H1b and H1c cannot be verified.

Table 1.2 Results by ordered logit model

	CH	US	SW	MX	KR	JP
PB	0.45**	0.22	0.04	− 0.07	0.20	0.40
PR	−0.26	−0.09	−0.07	0.19	−0.18	−0.03
PQ_c	1.78***	1.79***	1.97***	2.60***	2.02***	2.09***
TSt_1	5.01***	4.49***	5.29***	7.61***	4.88**	6.06***
TSt_2	7.03***	7.05***	8.43***	10.39***	7.86***	8.89***
N	152	151	150	150	150	150
R^2	0.20	0.21	0.22	0.30	0.25	0.30

Note The response variable is the purchase intention toward country *c*'s CBEVs (PI_c). "*c*" means China, the US, Sweden, Mexico, South Korea, and Japan. Asterisks (**, ***) indicate that the estimate is significant at 5% and 1% levels, respectively. TSt_1, t_2 correspond to Threshold t_1, t_2. R^2 is Pseudo R^2. Control variables are included in each model

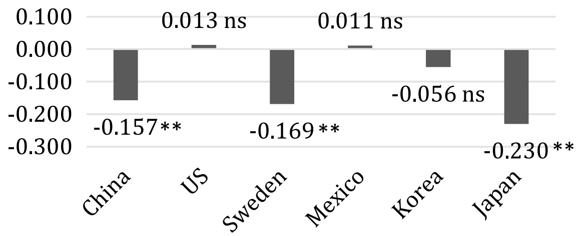

Fig. 1.1 Average marginal effects of ethnocentrism. *Note* Asterisks (**) indicate that the estimate is significant at 5% level. Values mean the average marginal effects of *ET* on the joint probabilities $\Pr\left(PI_c^A = 1, PQ_c^H = 1\right)$

1.4.1.5 Hypotheses H2a, b

We employ the bivariate probit model to estimate the effects of the ethnocentrism index (ET) on PQ_c^H and PI_c^A. The Wald test under the null hypothesis is ρ, the correlation between two bivariate outcomes, equals zero shows the significance probability is 0.000 for each bivariate probit model. Therefore, the null hypotheses are rejected.

Figure 1.1 indicates the average marginal effects of ET on the joint probabilities $\Pr\left(PQ_c^H = 1, PI_c^A = 1\right)$ of six countries. For example, when a respondent has the high level of American ethnocentrism, the probability of the person who perceives Chinese CBEVs as a high-quality product and intends to purchase a Chinese CBEVs decreases by 15.7%. The signs of the average marginal effects are significantly negative on Chinese, Swedish, and Japanese CBEVs' evaluations. These results support the hypotheses H2a and H2b.

1.5 Conclusion

1.5.1 Study Summary

This study assesses the importance of constructs related to attitudes towards CBEVs. The identified constructs are then entered into a hierarchical regression analysis which uses either positive or negative evaluations of the instrumental capabilities of EVs as the dependent variable. In general, this research has found that the perceived product quality of CBEVs made-in various countries has a substantial impact on consumers' purchasing behavior (H1a), but not perceived benefits or risks (H1b, H1c). This study finds that consumer ethnocentrism affects perceived product quality and purchasing behavior towards CBEVs. While the study observed the high-ethnocentric US consumers' preference to the CBEVs made-in the US (H2a), the US consumers rated CBEVs made-in China, US, and Japan in the same group. The study found that the low-ethnocentric US consumers are willing to purchase the

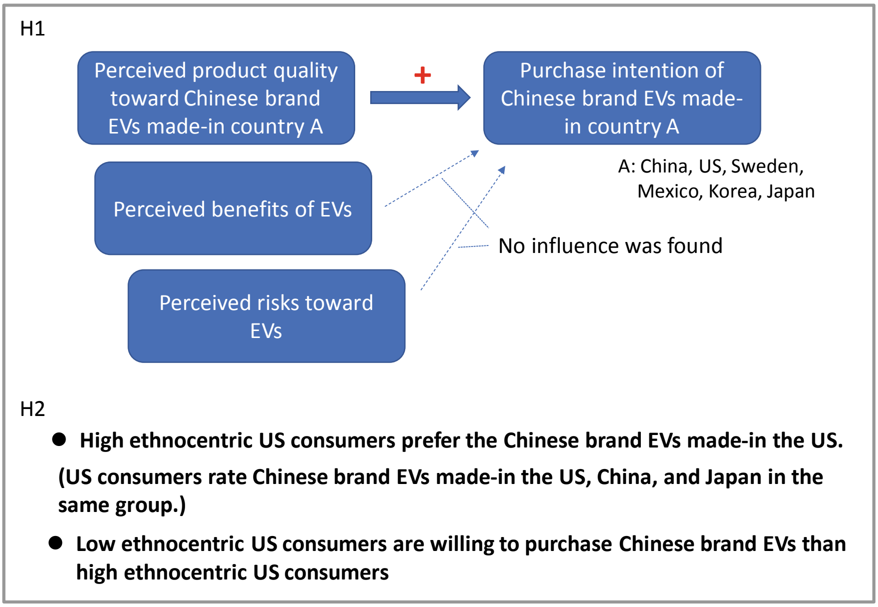

Fig. 1.2 Hypothesis testing summary

CBEVs made in China and advanced countries than those who are high-ethnocentric consumers (H2b). Figure 1.2 provides a summary of hypothesis testing in this study.

This study examines the US consumers' purchase intention on CBEVs made-in various geographical locations: US, China, Sweden, Mexico, India, South Korea, and Japan. We found that product quality influences the purchase intention of the CBEVs. While the study observed the high-ethnocentric US consumers' preference to the CBEVs made-in the US, the US consumers, in general, rated CBEVs made-in China, US, and Japan in the same category. Comments expressed by respondents in this study explain relatively high rating for the CBEVs made in China:

> If the car is reliable, affordable, and better for the environment, I would buy the car regardless of brand and location of production.
>
> China produces and manufactures many products that Americans use daily.
>
> I think China has the technology and knowledge to make efficient EVs.

1.5.2 Plant Location

Plant location is an important factor because it affects the cost, selling price, and demand for products and determines the performance of an organization. Despite the low evaluation reported in this study, Mexico has clear offshoring advantages of manufacturing over South Korea, Sweden, and India in open trade and proximity to the US market. However, a major concern for choosing Mexico as a production location at present is the possibility of being targeted by the US administration. For example, US President Trump has criticized the Japanese automobile industry that automobile trade between Japan and the US is unfair. On January 5, 2017, Mr. Trump tweeted as the following: "Toyota Motor said it would build a new plant in Baja, Mexico, to build Corolla cars for U.S. NO WAY! Build a plant in U.S. or pay big border tax" (Trump 2017). Trump's tweet caused Japanese automobile makers positioning Mexico as the export base to the US market to revise their manufacturing strategies.

If indeed China builds plants of EVs to target the US market, the US is a clear choice. If the US restricts CBEVs made in China, and if Chinese EVs manufacturers build plants in the US, China may be receiving lasting benefit. For instance, several Japanese companies (e.g., Toyota) accelerated plans to build assembly plants in the US by two to four years as a result of the US protectionism trade policy in the 1980s. Currently, Japanese car manufacturers produce 3.8 million cars in the US. Chinese EVs manufacturers may receive substantial benefits from the investment EVs production facilities in the US. In the end, a new competition, not the restriction of competition, will accelerate the US EVs industry.

1.5.3 Strategic Recommendations for CBEVs

In just a few decades, dramatic changes in the demographic, natural, economic, social, legal, and political environments, combined with modern advancements in batteries technology, new energy sources, and AI technology will revolutionize most competitive environments for the EVs. The competition will become global, rather than mostly domestic. That is, China, like any other new entrant in the US market, will face with well-established competition amongst the US and foreign EV manufacturers. To gain market share in the US, China needs to perform activities that increase the value of products deemed necessary by customers. This is important not only because of the price aspect but also due to the establishment of "the value [US] consumers associate with a [Chinese] brand, as reflected in the dimensions of brand awareness, brand associations, perceived quality, and brand loyalty" (Aaker 1991). Entering the US market requires strong promotional support because customers are reluctant to purchase, or even consider, a product with which they are unfamiliar. Prospects with interest in a new product are not likely to turn into actual buyers until they experience the comfort of familiarity.

In order to increase US consumers' familiarity with CBEVs and accelerate their brand-building efforts, we suggest that CBEVs form strategic alliances with western companies possessing resources and core competencies such as brands, technologies and distribution networks. According to the signaling theory, when certain attributes of a product, a service or a person are not directly observable, one party, the agent, may credibly convey some information about itself (him or herself) to another party, the principle (Spence 1973). While the US consumers may have little knowledge about the CBEVs' quality, their western alliance partners' existing reputation serves as a credible signal. Recently, Qiantu Motor, a wholly owned subsidiary of China-based CH-Auto and Mullen Technologies Inc., a Southern California company, have signed a cooperation agreement to homologate and assemble electric sports cars in the US for sales in North America (Eisenstein 2019). Similar alliance strategies have proven to be effective in other industries. For example, one of China's leading smartphone makers, Huawei, has quickly increased its brand equity by collaborating with German companies Leica (on camera technology) and Porsche (on product design). Despite a decade-long separation between Huawei and the US, Huawei has become one of the world's most valuable brands by both Forbes and Interbrand. When CBEVs form strategic alliances with western companies, they not only gain immediate access to their partners' technologies and distribution resources, but also benefit from their brand equity.

1.5.4 Ethnocentric Beliefs and COO

This study shows that low-ethnocentric consumers are more likely to use COO cues as objective information about product quality. In contrast, high-ethnocentric consumers use COO information to express ethnocentric sentiment and are influenced by this in their purchase decisions (Klein 2002). Moreover, this study shows that high-ethnocentric consumers tend to believe that domestic products are of higher quality than comparable imported ones. The US consumers who hold low-ethnocentric views about the EVs made-in foreign countries feel that their purchase of foreign EVs is perfectly appropriate in general. However, they are reluctant to buy the EVs of a specific country.

Chinese products have long been associated with their cheap prices and low quality. However, China has been investing heavily in R&D in recent years (Gross 2013), trying to encourage its talent to stay home, and creating the flow of knowledge and young Chinese talent back to China (Grossman 2010). Instead of toys and shoes, shiny drones, smartphones, and other technological products may come to minds of some the US consumers. This study has observed the US consumers' relatively high-purchase intention towards an eco-friendly and high-tech product, an electric vehicle.

Based on our findings that low-ethnocentric consumers are more likely to use COO cues as objective information about product quality and the US consumers rated CBEVs made-in China, US, and Japan in the same group, we suggest that CBEVs primarily target low-ethnocentric consumers, especially in the early years of their entry into the US market, as these consumers are less likely to stereotype CBEVs. While consumers' ethnocentrism may not be directly observable, further research may reveal the correlation between the level of ethnocentrism and variables such as age group, educational level, and region of residence. For example, if further studies find that the younger generations, consumers with higher educational levels, and consumers living in metropolitan areas on both the east and west coasts show a significantly lower level of ethnocentrism, then CBEVs should focus their marketing efforts on these consumers to accelerate their penetration into the US market. Once they have established a firm foothold in these target groups, the CBEVs may subsequently penetrate consumer groups with higher levels of ethnocentrism.

Manufacturers should mention both COO information and eco-certification in the case of green products made-in a country with a positive ecological image (Dekhili and Achabou 2015). This is because communication about the ecological image of the COO could help to differentiate a country, reinforcing the credibility of some offers and making imitations difficult. The future study can include ecological image and eco-certification. Credible quality certifications can provide consumers with direct signals of product quality, and thus they can help reduce the consumers' perceived risks of remanufactured products (Matsumoto et al. 2018).

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Chapter 2
Comparative Analysis of the Users' Kansei Evolutions Over Their Short and Long-Lived Products' Lifetimes in Iran

Seyed Javad Zafarmand

Abstract Indeed, a sustainable product ought to be able to last throughout its expected lifetime not only objectively, but subjectively. The concept of Product Subjective Sustainability (PSjS) is to address 'a product capability to age emotionally/affectively/aesthetically and last satisfyingly and pleasantly during its expected long/short lifetime'. Using Kansei Engineering approach, in order to approach PSjS experientially, this paper presents the results of an analytical study on the evolution of Iranian users' Kansei comparatively respecting their short-life and long-life products during the entire lifetimes of these products. The short and long lived product types specified for this research are respectively mobile phone, private passenger car and traditional handicraft.

Keywords Product subjective sustainability · Psychological lifetime · Mobile phone · Passenger car · Handicraft

2.1 Introduction

The studies regarding sustainability are mostly done on its objective aspects, whereas its subjective side have not been observed adequately (Hart 1994, 1995), though the importance of subjective aspects of sustainability has been reinforced within some scientific debates (Douven et al. 1995; Fricker 1998; Stirling 1999; Jacob and Brinkerhoff 1999; Kemp and Martens 2007). The key challenge of "subjective environmental aspects of products and processes" has been discussed in design research since the last years of the 20th century (Hoffman 1997). Nevertheless, the importance given to the subjective issues of sustainability within design research has been increased (Childs et al. 2006). The focus of design research concerning such issues is on 'lifetime optimization of products' (Nv and Cramer 2003). Nes and Cramer proposed five design strategies for product longevity among which 'product attachment' seems to

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be the most directly related to the product's psychological or subjective lifetime (Nes and Cramer 2005).

As emotional bonding may increase a product's lifetime (Mugge et al. 2009), extending the psychological lifespan of durables and increasing the degree of consumer-product attachment could be instrumental in reducing both the demand for scarce resources and the rate of solid waste disposal and may contribute to a more sustainable society (Hinte 1997; Mugge et al. 2004; Govers and Mugge 2004; Schifferstein and Zwartkruis-Pelgrim 2008). The strategy of enhancing product attachment, however, brings many challenges (Nv and Cramer 2003). According to the author's previous researches' findings, there are at least two other effective trends than just product attachment that could be used for extending the psychological lifetime of such short-lived product as mobile phone (Zafarmand et al. 2009a, b). In fact, the important subjective issues about a product may include the user's total attitude, feeling, affection, emotion and/or appreciation in addition to user-product attachment. Such subjective issues could be professionally called Kansei (Childs et al. 2006; Lee et al. 2002; Schütte et al. 2008) rather than any other term like emotion.

The term 'subjective sustainability' has been used as a versatile and wide concept in the literatures of various fields such as social sciences (Becker and Jahn 1999) public policy (Tierney 2003), forest management (Smith et al. 2001), urban design (Jacob and Brinkerhoff 1999; Kemp and Martens 2007; Castello 2006; Gosh and Vale 2009) and package design (Salazar 2008). Nonetheless, the definite territory of 'subjective sustainability' has not been identified clearly or explained well within the literature.

Within the author's previous research, as the initiation of this research, "a product's capability of being pleasing, appealing and satisfyingly enduring during its expected long/short lifetime" particularly was named 'Product Subjective Sustainability' (PSjS). Nevertheless, PSjS could be expanded to generally embrace all subjective issues of how a product reflects or affects sustainability values (Zafarmand et al. 2011). This concept was first proposed at IASDR 2009 conference (Zafarmand et al. 2009) and then expanded at EcoDesign 2009 international symposium (Zafarmand et al. 2009).

2.2 Framework

In this research, the evolution of users' *Kansei* toward their short/long-lived products over the entire lifetime of products is analyzed in order to clarify PSjS through *Kansei* Engineering approach (Lee et al. 2002; Schütte et al. 2008). The entire lifetime of the product from the user's perspective is here divided into three main lifecycle stages: Purchase (P); Keep or Use (KU); and end, throw away or Replace (R). This framework is to approach PSjS experientially and expand it analytically.

Considering the following points, mobile phone, private passenger car and traditional are designated, respectively, as the short and long-lived product cases for this analytical study. First, the subjective issues of mobile phone are more considerable than other kinds of products due to the users' very close/personal relationship with it despite it being a short-lived product (Zafarmand et al. 2006a, b). A user's emotional attachment to a mobile phone—rather than other kinds of products—has been reflected in numerous scholarly works (Vincent 2005, 2006; Wehmeyer 2007, 2008). Second, there is a considerable level of attachment between a user and his/her own car (Govers and Mugge 2004). Private passenger car is an approximately long-lived product. As a private passenger car registers its owner's individual character and social class, a user may have a personal relation with his/her car. Third, the traditional handicraft is definitely a long-lived product, which is very valuable and respectable for its owner considering its rich cultural aspects. Nevertheless, these three kinds of product completely vary when considering their function, technology, mobility, status, background and scale beside the user. Within the author's previous research, the patterns of three groups of Japanese users' *Kansei* evolution over the lifecycle stages of their mobile phone, car and handicraft/furniture were extracted separately and compared between these products (Zafarmand et al. 2010, 2012). Furthermore, to comparatively show the trends of PSjS between the short/long-lived products, the responds of these three groups of Japanese subjects were analyzed all together (Zafarmand et al. 2011). In this research, the trends of PSjS would be compared between the short/long-lived products, but on the basis of the responds of three groups of Iranian subjects, as the owners/users of the above-mentioned three product types, within the same way as the last one, in which the subjects' responds regarding the product types are analyzed all together. Finally, the findings and the trends of PSjS would be compared between these two countries, Iran and Japan, to show the possible effects of contextual differences on PSjS.

2.3 Method

The required data for this research were gathered through the definite and descriptive questionnaires filled by three groups of Iranian subjects, as the user/owner of mobile phone, passenger car and handicraft. The subjects were asked to write down their feelings, emotions, images and/or attitudes—namely, their Kansei—regarding their products (mobile phones, cars or handicrafts) in each of the three lifecycle stages (P, KU and R) separately into three different questions.

The first group of subjects, users of mobile phone, were 71 persons ranged from 16 to 28 years old, were 77% female and 23% male and consisted of 50 university students at University of Tehran, Iran University of Science and Technology and Shiraz University and 21 high school students living in the city of Shiraz. The second group of subjects, owners of private car, ranged from 25 to 73 years old, were 30% female and 70% male and consisted of 30 users of private car living in the city of Tehran or Shiraz. And the third group of subjects, owners of handicraft, ranged from 20 to 70 years old, were 65% female and 35% male and consisted of 26 users/owners of handicrafts living in the city of Tehran or Shiraz.

The descriptive words that the subjects used to describe their Kansei about their products in the lifecycle stages were summarized into Kansei items through the KJ Method (Kawakita 1986; Ohiwa et al. 1990). The Kansei items based on the subjects' responses were processed by using Quantification Theory Type III (QT3) (Hayashi and Suzuki 1975) to show their distribution in three dimensions on X, Y and Z axis and, accordingly, their major trends. This number of axes for the spatial data derived from QT3 was decided on the basis of the resulting Eigen values which were more than 0.500. The distribution of the subjects' Kansei statuses in the three lifecycle stages of their products would be another output of this QT3 process. To show the trends of the subjects' Kansei evolutions over their short/long-lived products' lifetime, the parameter of Centers of Gravity (CG) of the spatial data relevant to the subjects' Kansei statuses in the three lifecycle stages of their products was used as the indictor. Finally, first, the resulting PSjS trends would be compared between the short and long lived products, and second, these findings would be compared with the trends derived from the last research done on the Japanese subject (Zafarmand et al. 2011).

2.4 Results

2.4.1 Kansei *Items Distribution*

In total, respectively, 635 Persian keywords (including 224 for the P stage, 219 for the KU stage and 190 for the R stage), 398 Persian keywords (including 125 for the P stage, 104 for the KU stage and 169 for the R stage) and 543 Persian *Kansei* keywords (including 227 for the P stage, 173 for the KU stage and 143 for the R stage) were derived from the subjects' responses regarding their *Kansei* about their mobile phones, cars and handicrafts in the different lifecycle stages of these products. All of these keywords were summarized into 82 *Kansei* items or descriptive keywords through the KJ method.

The subjects' responses about their *Kansei* regarding all three lifecycle stages of their products were adapted to these 82 *Kansei* items and processed by using QT3. The overall output distributions of the *Kansei* items are shown as X–Y and X–Z graphs in Fig. 2.1. On the basis of the context and distribution of the *Kansei* items in the graphs, the three axes of X, Y and Z are, respectively, named '*Pleasance–Pain*', '*Active Emotion–Passive Affection*', and '*Subjective–Objective*'. The *Kansei* items, their resulting X, Y and Z dimensions and frequencies in each lifecycle stage and product type are presented in Tables 2.1 and 2.2. The *Kansei* items, which are specified for only one of the stages of P, KU and R, are shown in Table 2.1, and the rest ones being relevant to more than one stage are in Table 2.2.

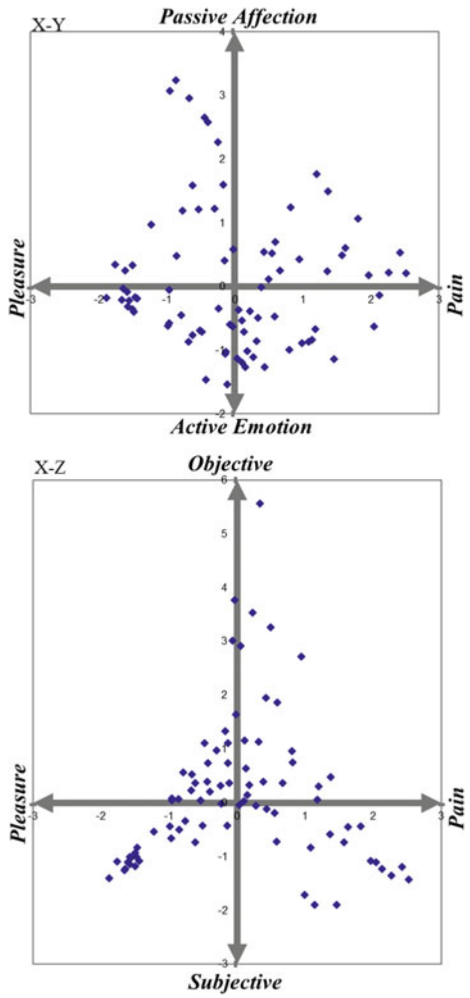

Fig. 2.1 Distribution graphs of the resulting *Kansei* items

2.4.2 **Kansei** *Evolutions Over the Products Lifetime*

In addition to the *Kansei* items' dimensions and the resulting distribution graph, the other output of this analysis is the spatial data representing the Iranian subjects' *Kansei* statuses during P, KU and R lifecycle stages of their products. As the spatial data relevant to the resulting *Kansei* items and the one representing the subjects' *Kansei* statuses are the "sample score" and "category score" derived from of QT3 analysis on the same input data, the same names could be given to the axis directions of their distributions graphs.

Table 2.1 The *Kansei* items specified for only one stage and their frequencies in each lifecycle stage and product type

Kansei items	QT3 output			*Freq. in stages*			*Frequency in*			Total
	X	Y	Z	P	KU	R	*Phone*	*Car*	*Craft*	*Freq.*
Techno-advantage	0.1	−1.2	0.0	24	0	0	13	8	3	24
Mod-Replace-think	2.1	−0.1	−1.2	22	0	0	2	13	7	22
Longevity	0.4	−1.3	−0.1	19	0	0	2	13	4	19
Nostalgic	1.0	−0.9	−1.7	19	0	0	0	1	18	19
Companion	0.6	−0.5	−0.7	14	0	0	1	7	6	14
Dislike/bad-feel	2.5	0.2	−1.4	14	0	0	0	6	8	14
Ordinary	2.0	−0.6	−1.1	11	0	0	1	8	2	11
Simplicity	0.0	−1.1	0.0	9	0	0	4	5	0	9
Confident	0.2	−1.3	0.1	8	0	0	3	5	0	8
Light	0.3	−1.1	−0.1	7	0	0	4	2	1	7
Big	2.0	0.2	−1.1	6	0	0	0	0	6	6
Expiring	1.5	−1.1	−1.9	5	0	0	0	2	3	5
Embarrassment	2.3	0.2	−1.4	4	0	0	0	1	3	4
Excited	−0.4	−1.5	0.7	4	0	0	4	0	0	4
Thirst/discovery	−0.1	−1.5	0.4	4	0	0	3	1	0	4
Unaccustomed	0.8	−1.0	1.0	4	0	0	3	1	0	4
Safety	0.2	−0.4	3.5	0	2	0	2	0	0	2
Unfit	0.3	−0.5	5.6	0	2	0	1	1	0	2
Gratitude	0.0	0.6	1.6	0	6	0	3	1	2	6
Handy	0.4	0.5	2.0	0	6	0	4	1	1	6
Modernity	0.0	−0.6	3.8	0	6	0	5	1	0	6
Doubt	0.9	0.4	2.7	0	7	0	6	1	0	7
Forward-looking	1.2	1.8	0.3	0	8	0	0	0	8	8
Facilities/quality	0.5	0.1	3.3	0	9	0	6	2	1	9
Retrospect	0.6	0.7	1.9	0	12	0	5	4	3	12
Happy-of-P	−0.1	−0.6	3.0	0	16	0	12	4	0	16
Comfortable	0.1	−0.4	2.9	0	17	0	8	7	2	17
Temporal	0.8	1.2	0.7	0	21	0	3	5	13	21
Antiquity	−1.6	0.3	−1.1	0	0	9	4	4	1	9
Appreciation	−1.8	0.3	−1.1	0	0	9	3	5	1	9
Beautifier/harmonic	−1.6	−0.1	−1.1	0	0	8	3	5	0	8
Content/philosophy	−1.5	−0.2	−0.8	0	0	10	6	4	0	10
Delicate	−1.6	−0.3	−1.0	0	0	8	4	4	0	8
Durable/no-boring	−1.5	0.3	−0.9	0	0	22	8	10	4	22

(continued)

Table 2.1 (continued)

Kansei items	QT3 output			*Freq. in stages*			*Frequency in*			Total
	X	Y	Z	P	KU	R	*Phone*	*Car*	*Craft*	*Freq.*
Form	−1.5	−0.4	−1.2	0	0	17	14	3	0	17
High quality	−1.6	−0.2	−1.0	0	0	18	11	7	0	18
Increasing value	−1.7	−0.2	−1.2	0	0	7	0	7	0	7
Laborious	−1.9	−0.2	−1.4	0	0	9	6	3	0	9
Natural	−1.6	0.0	−1.2	0	0	4	3	1	0	4
Original	−1.5	−0.4	−1.0	0	0	7	5	2	0	7
Seeking	−1.0	3.1	0.1	0	0	8	0	0	8	8
Self-blaming	−0.7	3.0	0.5	0	0	5	0	0	5	5
Tradition/culture	−1.4	−0.2	−1.1	0	0	17	11	6	0	17
Valuable	−1.2	1.0	−0.5	0	0	13	3	6	4	13
Woe	−0.9	3.2	0.1	0	0	12	0	0	12	12

2.5 Discussion and Conclusion

2.5.1 Trends of Kansei *Evolution*

Comparing the trends of subjects' *Kansei* evolutions between mobile phone, car and handicraft beside the axes directions of graphs (Fig. 2.2), the Iranian subjects' *Kansei* statuses in stage R roughly tend to the *Passive Affection* and/or *Pain* sides regardless to the product type. Regarding all product types, the subjects' *Kansei* statuses evolve from *Active Emotion* in stage P to *Passive Affection* in stage R. The subjects' *Kansei* status regarding such short-lived product as mobile phone in stage P tends to *Active Emotion* and borderline of *Pain–Pleasure* sides, while such a status regarding the long-lived products is gradually tending to *Passive Affection* and *Pleasure* sides. Accordingly, the gray arrow directed from quarters 4 to 2 in X–Y graph (Fig. 2.2) is to indicate the position of the users' *Kansei* evolutions based on the product lifetime. But, the gray dotted arrow, which is directed from quarters 3 to 1 in the same graph oppositely, is to show the general pattern of users' *Kansei* evolution over the products' lifetime from start to end. The subjects' *Kansei* statuses in KU and R stages of their handicraft and somehow their car are seemingly close, probably due to the users' reasons and intentional circumstances of replacing private cars, unlike the other products.

Looking at X–Z graph (Fig. 2.2), the subjects' *Kansei* statuses regarding such definitely long-lived product as handicraft evolve from *Subjective* to *Objective*, while such trend is reverse in private car and mobile phone. In R stage, however, mobile phone tends to *Pain*, whereas car tends to *Passive Affection*. The subjects' *Kansei* statuses in P and KU stages of their handicraft are so close probably because a user's

Table 2.2 The *Kansei* items relevant to more than one stage

Kansei items	QT3 output			*Freq. in stages*			*Frequency in*			Total
	X	Y	Z	P	KU	R	*Phone*	*Car*	*Craft*	*Freq.*
Decreasing value	1.1	−0.9	−0.8	14	0	1	2	12	1	15
Broken/lost	1.1	−0.8	−1.9	10	0	1	0	2	9	11
Individuality	−0.6	−0.8	−0.7	12	0	9	11	7	3	21
Interest	−0.5	−0.7	−0.4	36	0	21	29	18	10	57
Good-look	−1.0	−0.6	−0.7	21	0	33	34	16	4	54
Prestige/social	0.2	−1.0	0.3	13	3	0	8	6	2	16
Variety	0.3	−0.9	1.1	7	3	0	8	1	1	10
Clean	−0.8	−0.5	0.6	0	3	2	4	1	0	5
Sorehead	1.4	1.5	0.5	0	3	2	0	2	3	5
Peace/relax	−1.0	−0.1	0.0	0	3	4	4	3	0	7
Pleasure	−0.7	−0.9	0.2	25	4	15	30	14	0	44
Appeal	−1.0	−0.6	−0.4	13	4	16	24	8	1	33
Riddance	1.6	0.6	−0.5	12	4	0	3	1	12	16
Repair/renew	−0.3	1.2	1.0	0	5	5	2	3	5	10
Regret	−0.4	2.7	0.4	0	5	10	0	0	15	15
Old/tattered	1.6	0.5	−0.7	17	6	1	0	7	17	24
Logical/habitual	−0.2	1.6	1.3	0	6	2	1	2	5	8
Tolerable	1.2	−0.7	0.1	28	7	0	11	21	3	35
Bored	2.4	0.5	−1.2	12	8	0	0	11	9	20
Accustomed	0.5	0.5	−0.2	8	8	0	0	10	6	16
Lost/missed	−0.4	2.6	0.2	0	8	9	0	0	17	17
Anxiety	0.7	0.3	0.4	28	9	7	18	9	17	44
Perfect/outstrip	0.1	−0.5	1.2	12	9	0	11	4	6	21
Reasonability	0.4	0.0	0.4	12	9	1	9	2	11	22
Proud/glory	−0.5	−0.7	1.1	10	9	6	17	7	1	25
Care-well	−0.6	1.6	0.4	0	9	15	4	7	13	24
Flaw/difficulty	1.4	0.2	−0.6	27	10	2	1	16	22	39
Novelty	−0.1	−1.1	1.1	19	10	4	27	6	0	33
Happy-of-R	1.8	1.1	−0.4	15	10	0	0	0	25	25
Cherished	−0.5	1.2	0.0	0	10	8	3	5	10	18
Utility/ease/needs	−0.2	−0.3	0.0	18	11	16	20	17	8	45
Memories	−0.8	1.2	−0.3	0	11	23	4	11	19	34
Love-attached	−0.1	0.4	−0.4	16	12	12	5	16	19	40
Friendship/relation	−0.8	0.5	−0.5	0	12	17	11	9	9	29
Good-feeling	−0.1	−1.0	0.7	42	14	7	35	23	5	63
Lonely-affected	−0.2	2.3	0.3	0	15	19	0	0	34	34

(continued)

Table 2.2 (continued)

Kansei items	QT3 output			*Freq. in stages*			*Frequency in*			Total
	X	Y	Z	P	KU	R	*Phone*	*Car*	*Craft*	*Freq.*
Satisfied	0.1	−0.7	0.6	33	16	3	12	33	7	52

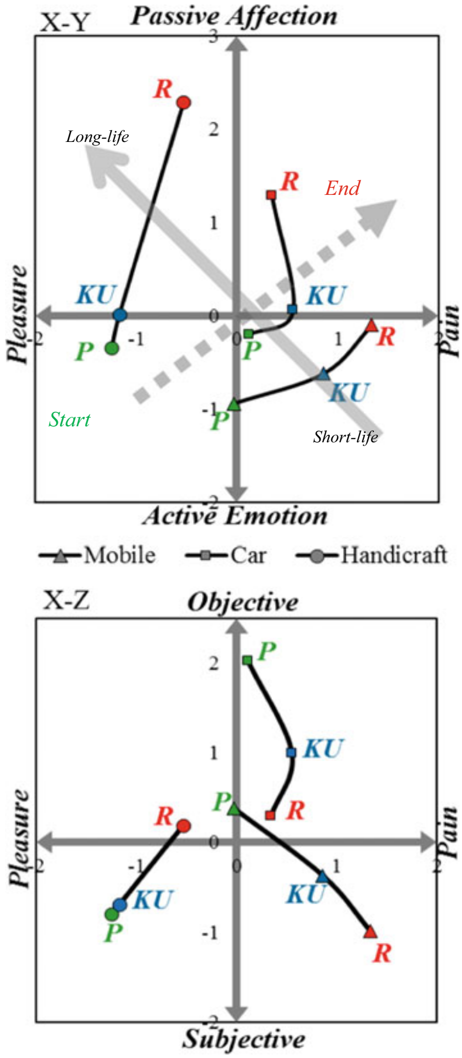

Fig. 2.2 Trends of Iranian subjects' *Kansei* evolutions over their mobile phone, car and handicraft lifecycle stages

attitude toward such a cultural/traditional object might have no drastic change in these two lifecycle stages.

2.5.2 Comparison

In order to compare the results of this research and the previous one (Zafarmand et al. 2011), namely the trends of *Kansei* evolution over the lifecycle stages of the products between the Iranian and Japanese subjects, as there is a symmetric similarity between the axes directions names in the graphs derived from the Iranian and Japanese subjects, the format of graphs derived from Japanese subjects' responses is considered the base. Accordingly, the axes' directions in the resulting graphs of Iranian subjects are adapted to the same order as the directions of the graphs of Japanese subjects. For this purpose, first, the Iranian subjects' output dimensions of X and Y axes are multiplied by "-1" and then, these two axes are replaced with each other. The adapted graphs of Iranian subjects' *Kansei* evolution over the lifecycle stages of their products are shown in Fig. 2.3, in which the trends of Japanese subjects' *Kansei* evolution over their products are kept in the background into gray.

As the first axis, namely X, is defined on the basis of the eingenvector resulted from QT3 analysis, and since eigenvalues indicate the significancy, the most significant trends of users *Kansei* evolution over their products' life in Iran and Japan are respectively, '*Pleasance–Pain*' and '*Passive Affection–Active Emotion*'. Such a point may imply that the Iranian users' responded *Kansei* words regarding their products have mostly an evaluative theme, whereas the Japanese users' responded *Kansei* words regarding their products have mostly a descriptive nature. In order to more clearly present the general trends of users' *Kansei* evolution over their short and long life products' lifecycle stages, these trends beside the directions of '*Active Emotion–Passive Affection*'/'*Pleasance–Pain*' (X–Y) and '*Active Emotion–Passive Affection*'/'*Subjectivity–Objectivity*' (X–Z) are separately shown in Figs. 2.4 and 2.5. In general, it seems users feel pleasure at the start of using their products, as they have gained somethings, and suffer or experience emotional pain at the end of their product lifetime, as they have last some values, regardless to the context and the product type.

As Fig. 2.4 shows, the general trend of users' *Kansei* evolution over their products' lifecycle stages tends to be laid in the '*Pleasure–Passive Affection*' area or the 2nd quarter of the X–Y graph regarding the long-lived product like handicraft, whereas such a trend regarding the short-lived product like mobile phone tends to be laid in the '*Pain-Active Emotion*' area or the 4th quarter of the X–Y graph. The amount of pleasure experienced during the product lifetime has seemingly direct relation with the length of the product life.

When considering the product type, however, the users may experience some doubts and problems when purchasing their cars or mobile phone as well as some troubles or problems at the first stages of use until they become accustomed to the operation and function of their cars or mobile phone. That is why the users' *Kansei*

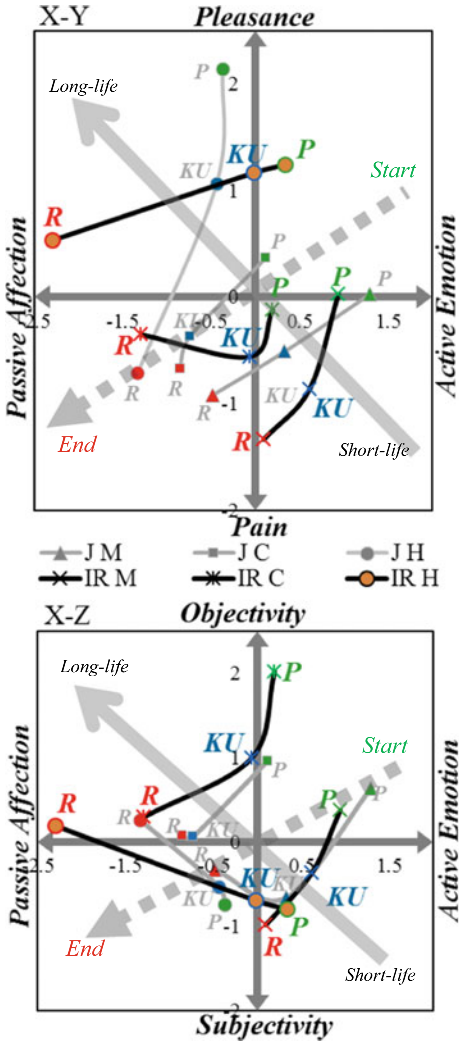

Fig. 2.3 Comparison of the trends of *Kansei* evolution over the lifecycle stages of mobile phone (M), car (C) and handicraft (H) between the Iranian (IR) and Japanese (J) subjects

status in P and KU stages of their mobile phones and cars seem to be obviously less pleasant than of their handicrafts. Nevertheless, it doesn't mean that the users feel absolutely no pleasure when obtaining and using a mobile phone or car, as they never purchase a product causing their emotional pain. There is also the factor of relativity, as the users' *Kansei* statuses in P stages of mobile phones and cars are more pleasant or less painful than those in R stages.

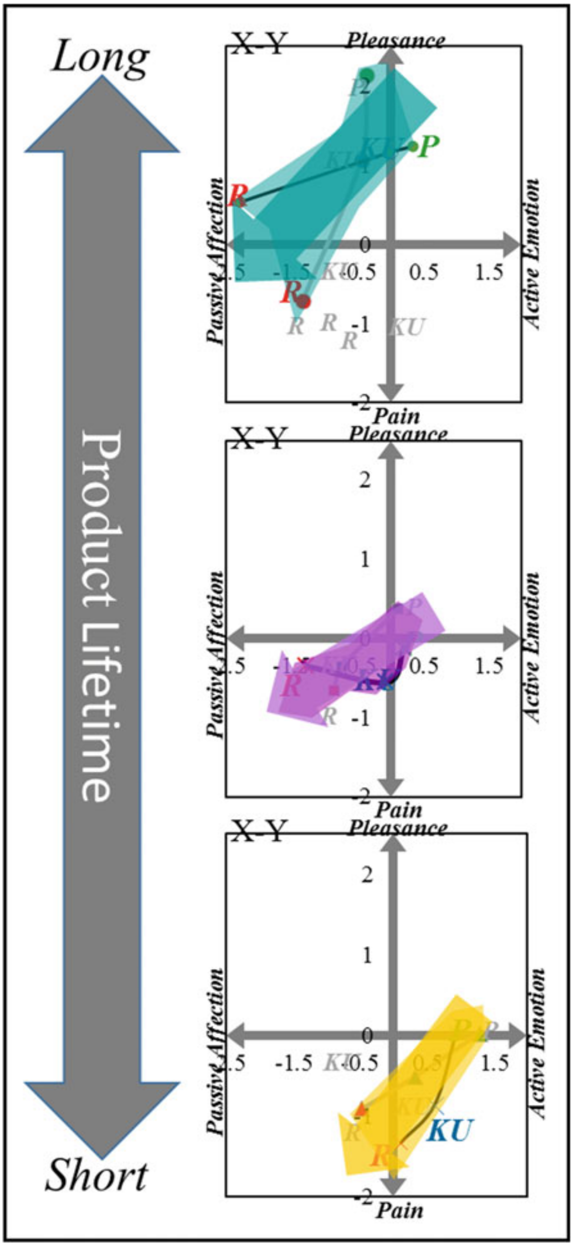

Fig. 2.4 Comparison of the general trends of users' *Kansei* evolution over their short and long life products' lifecycle stages beside the directions of '*Active Emotion–Passive Affection*' and '*Pleasance–Pain*' (X–Y)

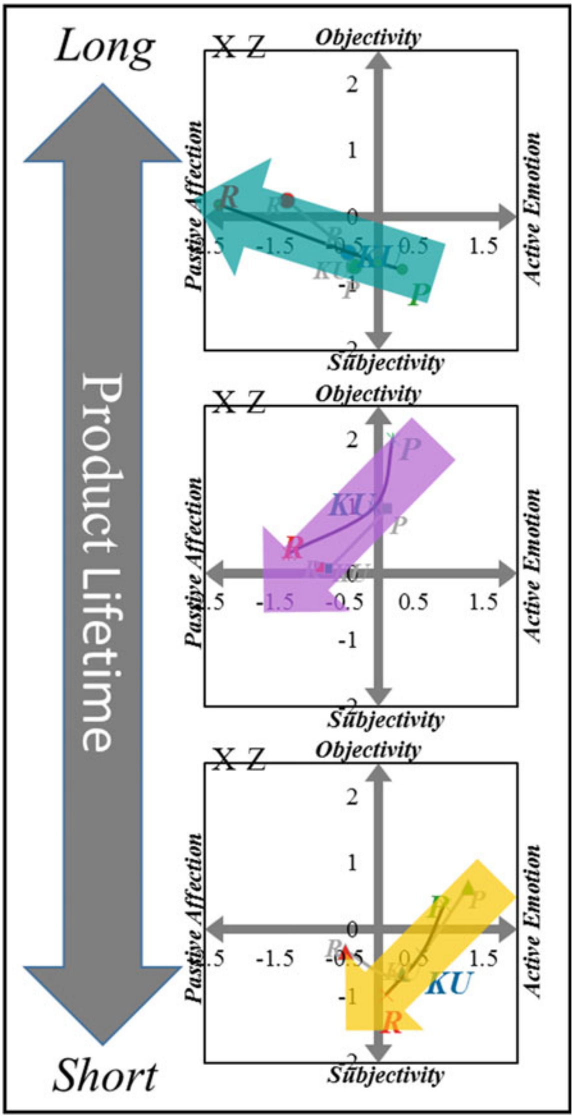

Fig. 2.5 Comparison of the general trends of users' *Kansei* evolution over their short and long life products' lifecycle stages beside the directions of '*Active Emotion–Passive Affection*' and '*Subjectivity–Objectivity*' (X–Z)

As Fig. 2.5 shows, the trend of *Kansei* evolution over the lifecycle of handicraft tends from subjectivity to objectivity, regardless to the context. But, such a trend regarding mobile phone and car oppositely tend from objectivity to subjectivity, probably due to the basic difference between handicrafts and the other industrial products and also the circumstances of product purchase, use and disposal.

2.5.3 Conclusion

Overall, there is a general similarity between trends of the Iranian and the Japanese subjects' *Kansei* evolution over the lifecycle stages of their products, despite the small differences of these trends. It seems, generally, in both contexts, a user's *kansei* regarding his/her short/long lived product would evolve from the status of active emotion, pleasure and objectivity to the status of passive affection, pain and subjectivity. Regarding the product type from length of lifetime perspective, in both contexts, users' *Kansei* evolution tend to be laid in active emotion, pain and subjectivity area over a short-lived product lifetime, and in passive affection, pleasure and objectivity area over a long-lived product lifetime. Therefore, handicrafts seem to give much more pleasure in comparison with mobile phone and car. In order to change the trends of *Kansei* evolution over the lifecycle stages of mobile phone and car to make them close to the pleasure side, some especial attributes of handicrafts such as individuality and cultural value could be helpful to be used or met in their design process. Shortening the time of users' accustomedness to the products by a good design is the other means in this regard. Product semantic, product language, affordance, integration, simplicity and customization could be effective for realizing such a good design. Furthermore, it seems so crucial to find out the design elements associating with the good *Kansei* items in the lifecycle of mobile phone and car. Thus, it could be a theme for the future plan and the extend of this research.

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Chapter 3
A Toolkit for Designing Products and Services Fit for Circular Consumption

Oskar Rexfelt and Anneli Selvefors

Abstract This paper introduces *the Use2Use design toolkit*—a set of tools that can be used to design for circular consumption. In contrast to other available circular design tools, the toolkit emphasises the importance of applying a user perspective when exploring opportunities for product circularity. It aids designers and other agents to explore user needs, identify consumption-related design challenges, and design products and services that can create enabling preconditions that make it possible, more convenient, and preferable for people to circulate products from use to use. The process to develop the tool is initially presented followed by a description of the toolkit and its five tools. The paper concludes with a discussion regarding how the proposed toolkit compares to other circular design tools and what implications it has for design practice and future research.

Keywords Circular design tool · Toolkit · User centered design · Circular consumption · Circular economy

3.1 Introduction

Recent literature on design and the circular economy has highlighted the crucial role design plays for a transition to a circular economy. It is often suggested that the transition requires products that are designed to last long, are fit for circular (re-)production flows, and are offered through circular services [see e.g. Bakker et al. (2014), Bocken et al. (2016)]. During the last couple of years, several circular design tools have been released aimed to support the exploration of such design opportunities. For instance, tools such as The Circular Design Guide (IDEO, Ellen MacArthur Foundation 2017), The Circular Economy Toolkit (Evans and Bocken 2013), Business as Unusual (Makatsoris et al. 2017), a tool for assessing remanufacturing from the customers' perspective and the Circular Pathfinder (Almefelt and

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Rexfelt 2017) offers worksheets and/or online platforms that can aid designers to explore different types of design opportunities.

A common denominator amongst these and other proposed tools is that they primarily focus on design opportunities related to production processes and/or business models. While such opportunities are essential to address to bring about a transition to a circular economy, opportunities to support changes in consumption are equally important (van Dam et al. 2017; Kirchherr et al. 2017). A transition to a circular economy is dependent on that people shift from linear consumption processes (i.e. buying new products, using, and disposing of them as trash) to circular consumption processes (i.e. obtaining pre-used products, using, and passing them on to others). Circular consumption (such as renting, borrowing or buying second hand) often requires new activities and entails different practicalities compared to linear consumption, which may sometimes make people refrain from obtaining pre-used products or passing them on (de los Rios and Charnley 2016). Hence, if aiming to support changes in consumption through design it is crucial to gain an in depth understanding of people's consumption processes and what they entail for everyday life.

Although available circular design tools either implicitly or explicitly take (some) aspects related to consumption into consideration, such as circularity-related behaviours and factors influencing acceptance of circular offers (Selvefors et al. 2019), they do not sufficiently address the changes in activities and practicalities that circular consumption often entails. Instead of highlighting the crucial role people play for product circularity, available tools often merely consider people as recipients of circular offers that should adopt circular behaviours. As a consequence, important design opportunities to support circular consumption, such as designing products that make it easy for people to inspect, value, or disassemble a product, are often overlooked (de los Rios and Charnley 2016).

The aim of this paper is to introduce a new circular design toolkit that have been developed to especially address people's consumption processes and the design challenges they entail. Following a brief method overview, the toolkit and included tools will be presented and the contribution as well as implications for design practice and future work will be discussed.

3.2 Method

The toolkit proposed in this paper is the result of an explorative and iterative process that began in 2013. The process was initiated with an explorative workshop in which seven researchers in the fields of user-centred design and sustainable design explored how product circularity could be framed with the user taking centre stage. Already existing and common representations of product circularity were examined in order to obtain an understanding of how users were represented in these, and to confirm the need for a new representation. A new user-centred perspective on product circularity, *the Use2Use-perspective*, was then developed during the following years. For a detailed description see (de los Rios and Charnley 2016; Camacho-Otero et al. 2019).

In 2016, the work to embody this perspective into a design toolkit was initiated. First, different potentially valuable tool components, covering e.g. analysis of use and ideation support, were developed. These early versions of the tools were used as a basis for exploring what content that would be valuable to designers and other relevant agents.

The initial tools, as well as their subsequent iterations, see Fig. 3.1, have been explored and evaluated through three main research activities during 2016–2019. First, workshops were conducted during 2016 and 2017 with designers, product developers and product managers from six companies (in total four workshops, each with 6–8 company representatives) to verify the need for the toolkit and to identify the requirements on it. The workshops were arranged in collaboration with the Swedish companies Transformator Design and Hultafors Group. The participants were asked to explore circular consumption design opportunities related to their product and service offers aided by early versions of the tools. The generated ideas and the participants' experiences of using the tools were discussed afterwards, both by the participants and the workshop organisers, and also analysed by the research team.

Second, refined versions of the tools were tested in workshops with design students in courses on Sustainable Design at Chalmers University of Technology (altogether on six occasions during 2017–2019, each with circa 30 students). The tasks were to gain an understanding of what circular consumption entail for people and come up with innovative ideas to make circular consumption preferable. The generated ideas and the tools' potential to support idea generation in comparison to another tool which the students had previously used, the Ecodesign strategy wheel (Selvefors et al. 2018), were discussed afterwards.

Third, refined versions of the tools were also tested by design students in their master thesis projects (in total by 13 students in seven teams) to identify design opportunities and suggest design concepts. The thesis projects concerned the design of a mobile application for sharing (Brezet and van Hemel 1997), a digital platform for sharing assets within the culture sector (Chalandon and Lindborg 2019), an autonomous delivery droid for collaborative consumption (Lindgren and Trens 2019), a tent for a rental service (Janebäck and Kristiansson 2019), a sofa for a furniture subscription service (Hagman and Wendt 2018), earphones for a rental service (Rosman 2018), and cars for a sharing service (Philipson and Wallner 2017). The experiences of the thesis students were monitored throughout their projects and all students were interviewed retrospectively to gain insight into their use of the tools and the challenges and implications they had experienced.

Through these activities, insights regarding the tools' potential value and usability were gained from both academia and industry and opportunities to improve the tools were identified. The tools were adjusted accordingly and packaged into the toolkit proposed in this paper.

Fig. 3.1 Early versions of the proposed tools used during workshops with companies

3.3 The Use2Use Toolkit

The toolkit includes five mind-expanding packs designed to boost product circularity by aiding the development of products and services fit for circular consumption processes. The five included tools address the early phases of a user-centred design process and together they cover elicitation of user needs, specification of design challenges, concept generation and evaluation. The tools can be used consecutively but also independently of each other. As illustrated in Fig. 3.2, the five tools differ in a number of ways, e.g. in regard to their purpose, format, and expected outcome. The toolkit is freely available at www.use2use.se (from September 2019). The tools and their intended use are presented in Sects. 3.1, 3.2, 3.3, 3.4 and 3.5.

3.3.1 Use2Use Thinking Activation Pack

The purpose of *the Use2Use thinking activation pack* is to help designers and other relevant agents to focus on circular-consumption and related design opportunities. In particular, it is intended to convey a user perspective on product circularity, to complement the often prevalent production and business model perspective.

As can be seen in Fig. 3.3, the tool consists of a set of educational cards that each underline an important aspect related to the users' role in product circularity. All cards have a statement on the front side, e.g. "People don't care about business models", to spark curiosity. The quotes are elaborated upon on the cards' back sides, which present information regarding the topic of the quote. Each card can stimulate discussion and provide insights to the participants, but it does not emphasise any specific output besides this. Neither is there any specific procedure suggested for using this tool; the cards can be used in the way that they are believed to be most useful for the situation at hand, e.g. seminars, meetings, workshops etc.

3.3.2 Circular Journeys Exploration Pack

The Circular journeys exploration pack helps designers and other agents to chart user activities and experiences during circular consumption processes. It is intended to be carried out as an analytic workshop, where the participants use pre-defined pieces to map out consumption processes on a flat surface such as a table, see Fig. 3.4. It is possible to map out journeys that have been thoroughly researched through user studies, but also less explored journeys based on for instance the participants' own experiences. Future consumption processes can also be mapped using the tool, making it possible to 'prototype' potential circular consumption journeys.

The pack contains pre-defined pieces of different kinds. The most central pieces are the hexagonal activity cards, which constitute the backbone of every mapped

	USE2USE THINKING ACTIVATION PACK	CIRCULAR JOURNEYS EXPLORATION PACK	MULTIPLE USE-CYCLES EXPLORATION PACK	CIRCULAR DESIGNS IDEATION PACK	CIRCULAR DESIGNS EVALUATION PACK
PURPOSE	To accentuate circular consumption and related design opportunities	To aid companies to chart user activities and experiences during circular consumption processes	To aid companies to empathise with subsequent users and understand how their needs vary	To aid companies to envision products and services that enable circular consumption	To aid companies to assess circular product and service concepts
FORMAT	Learning and discussion activities, supported by educative cards	Analytic workshop, supported by a set of journey mapping pieces	Relay excercise, supported by empathisation cards	Creative workshop, supported by design strategy cards	Analytic discussion, supported by screening canvases
SUGGESTED PARTICIPANTS	Anyone, especially designers, strategists, managers, and policy makers	Designers, user researchers, product managers, and users	Designers, user researchers, product managers, product developers, and users	Designers, user researchers, product managers, and product developers	Designers, strategists, business developers, managers, and sustainability experts
NUMBER OF PARTICIPANTS	1-n people, depending on the type of activity	2-6 people	4-8 people	2-6 people	2-6 people
TIME REQUIRED	20-60 min, depending on format	1-3 hours	30-60 min	30 min - 2 hours	30-60 min
PREPARATIONS REQUIRED	-	User insights, and a flat surface min 1x2m^2	User insights, and a product or a representation of it	Identified consumption-related design challenges, and workshop material	Documented concept(s) to assess, and insight into preconditions for implementation
EXPECTED OUTCOME(S)	Optional: documented insights and user related design challenges	Documented insights and user related design challenges	Documented insights and user related design challenges	Documented design concept(s) and key benefits	Identified design concept(s) worthy of further development

Fig. 3.2 Overview of the five tools included in the Use2Use design toolkit

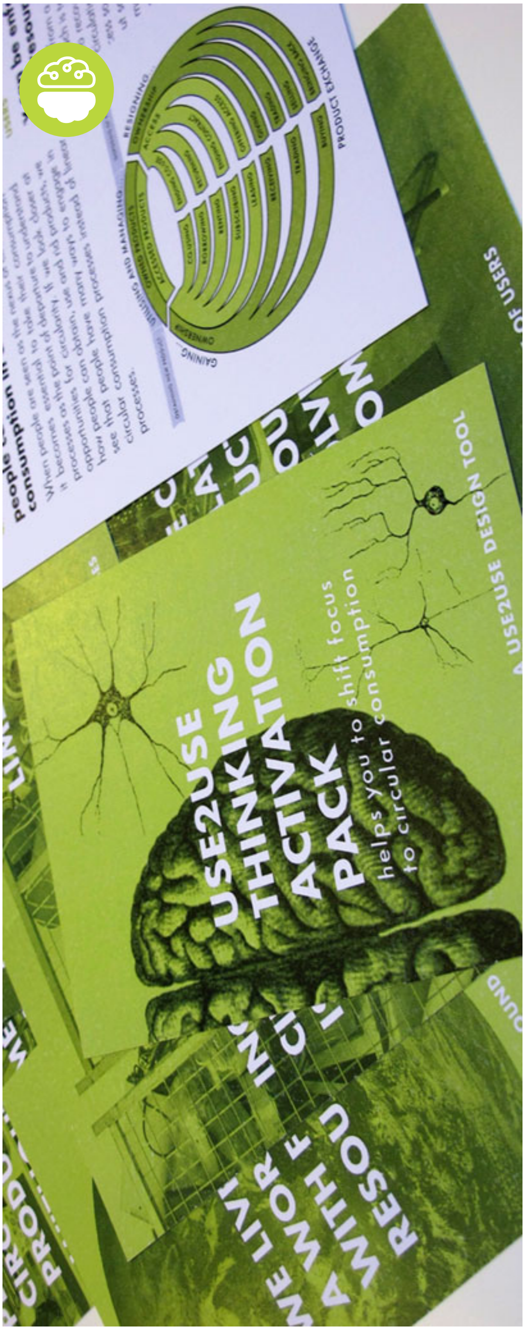

Fig. 3.3 The Use2Use thinking activation pack consists of a set of educational cards

Fig. 3.4 The circular journeys exploration pack consists of pre-defined pieces that can be used to chart people's consumption journeys

consumption journey. These pieces describe the main consumption activities such as "Explore obtainment opportunities", "Initiate product use" and "Prepare product for riddance". These pieces are specifically designed to cover the three main phases of consumption: obtainment, use and riddance. The pack also contains pieces to detail how these activities are carried out, and pieces to highlight important decisions for the user. In addition, there are pieces to indicate experiences that are typically considered negative or positive by the users.

By mapping circular consumptions journeys, user activities and everyday practicalities can be explored. Gaining an understanding of these aspects is key if one wants to improve consumer experiences related to circular consumption.

3.3.3 Multiple Use-Cycles Exploration Pack

The Multiple use-cycles exploration pack helps designers and other relevant agents to empathize with subsequent users and understand how their needs vary. "Subsequent users" refers to the fact that product circularity entails that product are circulated from user to user, something that other circular design tools and methods typically do not emphasise.

As shown in Fig. 3.5, the tool consists of a set of empathisation cards that each underline an important aspect that should be considered for products that are to be used by a sequence of users. Every card has a quote, e.g. "I have just obtained the

Fig. 3.5 The multiple use-cycles exploration pack consists of a set of cards that each underline an important aspect that should be considered for products that are to be used by a sequence of users

product from the previous user. I'm worried that parts of the product or its accessories are missing". The quote is followed by a number of questions to trigger discussion regarding the topic of the quote, and to support the identification of related design challenges.

The cards are intended to be used during an exercise in the form of a relay. A product to base the discussion on is first defined, and this product is then handed over between participants (preferably physically if the product is present and is small enough). Each time the product is handed over, the 'new user' draws a card and the topic of the card is discussed in relation to the product.

This tool can help identify problems and concerns related to sequences of users. In addition, it can unveil how certain activities that are carried out often during circular consumption processes make it important to re-prioritise the product requirements. For instance, a requirement that a product should be intuitive to use becomes even more important if the product is to be used by a new inexperienced user every day.

3.3.4 Circular Designs Ideation Pack

The Circular designs ideation pack helps designers and other relevant actors to envision products and services that enable circular consumption. The tool comprises design strategy cards for four areas related to circular consumption: "Extended use", "Product exchange", "Circular match-making", and "Multiple use-cycles" [for a more detailed description of these design strategies see (de los Rios and Charnley 2016)]. Each design strategy is described on a large card, which also contains trigger questions related to the strategy. The other side of the card shows an inspiring design example, i.e. a product or service in which the design strategy has been successfully incorporated. Figure 3.6 provides examples of some of the strategy cards.

The purpose of this tool is to spark ideas. It will help if the explorative tools (*the Circular journeys exploration pack* and *the Multiple use-cycles exploration pack*) have been used beforehand, so that one is aware of what consumption-related design challenges to focus on. It is however not necessary, since each card has a short introduction describing typical design challenges.

3.3.5 Circular Designs Evaluation Pack

The Circular designs evaluation pack helps designers assess circular product and service concepts. Each concept is evaluated from the point of view of three different stakeholders: the Users, the Organisation (e.g. a company) and the Environment. For each of the stakeholders, two aspects are evaluated. The first one is "potential", referring to the effects the concept will have for the stakeholders if it is implemented. The other aspect is "implementation", which refers to what is needed to successfully implement the concept.

Fig. 3.6 The circular designs ideation pack consists of a set of design strategy cards

As shown in Fig. 3.7, the tool consists of an A3-format canvas with a large matrix, in many ways similar to a Pugh-matrix (Kuikka and Swenne 2017). To aid assessment of the concepts from each stakeholder's point of view, supportive questions are included on the canvas. The canvas also has a section to mark all the concepts on a chart similar to a PICK-chart (Pugh 1981), often referred to as an impact-effort matrix. This way, all concepts can be compared regarding their potential effects, and the effort needed in the implementation process.

3.4 Discussion

The overall contribution of the proposed *Use2Use design toolkit* and its implications for design practice and future work will be discussed in this section.

3.4.1 Contribution

Since the toolkit has been developed to especially address people's consumption processes and the design challenges they entail, it complements previously proposed circular design tools in several ways. It is designed to aid the exploration of user needs and, as recommended by de los Rios and Charnley (2016), it provides support for conducting new types of user studies. Two of the tools, *the Circular journeys exploration pack* and *the Multiple use-cycles exploration pack*, can be used together with users to facilitate user needs elicitation. Through the use of these tools it will be possible to identify design challenges and product requirements that are essential to address in order for circular consumption processes to become more preferable compared to linear ones. For instance, although "facilitate cleaning" is an important requirement for most designs, it becomes even more relevant if a product is to be used for a long period of time by many subsequent users.

The proposed toolkit highlights new types of design opportunities and rationales for companies. In particular, it points to that companies do not have to develop business models with themselves as the nexus of circularity. Instead, they can develop products and services fit for circular consumption that enable products to be transferred from use to use. The toolkit also emphasises that design opportunities commonly framed from a production or business perspective can be addressed from a user perspective, which is often overlooked in other available tools. For instance, facilitating dis-assembly is a common strategy to enable circular production processes, but it may be just as important for users to be able to disassemble a product so that they can conveniently transport it to new users. From a design point of view, facilitating dis-assembly for users may be very different from facilitating dis-assembly in a production line. Hence, if a product is to be frequently shared, rented, or sold second-hand, it may be better to optimise the design so that it can be exchanged easily from use to use rather than to optimise it for re-production flows.

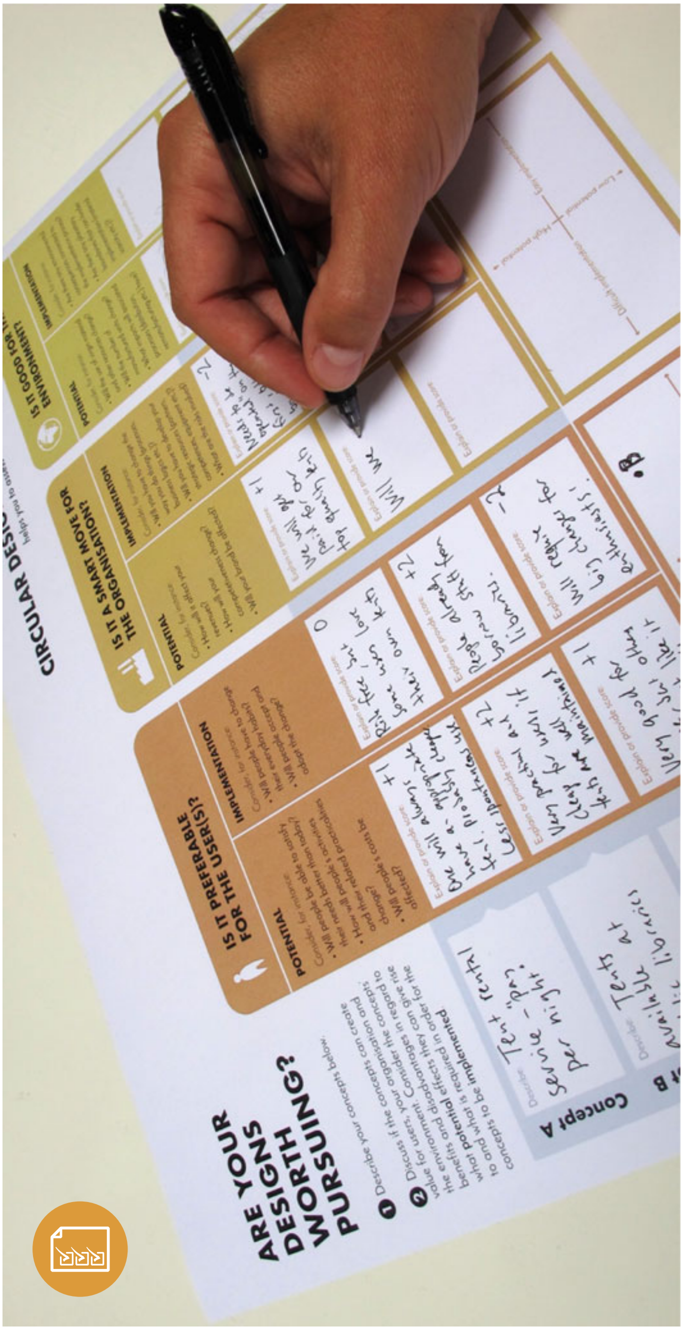

Fig. 3.7 The circular designs evaluation pack consists of a canvas with an assessment matrix

Lastly, it needs to be acknowledged that this toolkit only provides some of the tools that a company could (and maybe should) use to design for product circularity. Although using the toolkit may result in new insights about users, and novel ideas that could be attractive to people, one needs to ensure that these ideas are not disadvantageous, e.g. from a business or a sustainability perspective. These perspectives need to be considered as well, for instance by using other specialised tools to in-depth explore different business cases and conduct life-cycle analyses.

3.4.2 Implications for Design Practice

In practice, the proposed toolkit has potential to support design processes by aiding designers and other agents to apply a user perspective on product circularity. As described by de los Rios and Charnley (2016), a user-centred perspective on circularity entails reflecting on how the company can contribute to the consumers' processes, and not the other way around. The toolkit has potential to aid such design work in several ways. It includes an educational tool which helps designers and other agents to embrace a user perspective on product circularity, explorative tools that support user needs elicitation, as well as ideation and evaluation tools that support hands-on design activities with a user focus. The toolkit will hence facilitate user-centred design processes, i.e. development processes that proceeds with the user as the centre of focus (George 2003), aimed at developing new products and services for the circular economy.

The use of the toolkit can contribute to new successful designs in two main ways. First, by grounding the development of new products and services on user insights, the toolkit will increase the likelihood that the designs will be accepted and adopted by the target group and decrease the risk of market failure. Second, using the toolkit will also enable companies to increase their value propositions and provide products and services fit to compete on a future market where linear consumption has lost its momentum. Designing products so that they, for instance, become easier for people to sell on the second-hand market is not a priority among companies today, since it rarely makes the products more attractive when sold as new. However, in a future with fierce competition for resources, more people might contemplate how to pass their products on already before buying them, which in turn can make companies designing for people's circular consumption processes more competitive.

3.4.3 Future Work

The proposed toolkit in its current form provides new tools for designers to address product circularity from a user perspective, and the response so far has been highly positive from the practitioners and students who have applied it. It is however in need of additional testing and possibly also further development.

Additional testing will be conducted to explore the tools' usefulness, user friendliness, their fit with companies' current design processes and other tools in use, and their potential to contribute to new innovative designs fit for circular consumption. Activities to test the tools will be carried out with representatives from industry in upcoming research projects but also with design students.

In addition to further testing, future work will also include exploring if any additional tools are required in order to cover additional aspects relevant from a user perspective, which are not already covered by the proposed five tools. This work should, among other activities, include studying people's consumption processes in more depth to gain insights into other aspects that are relevant to address when aiming to design products and services fit for circular consumption.

3.5 Concluding Remarks

This paper introduces *the Use2Use design toolkit* which should be seen as complementary to previously suggested tools for circular design. In contrast to other tools, the proposed toolkit and its five tools provides support to explore circular design opportunities from a user perspective. The toolkit will specifically aid designers and other agents to embrace a Use2Use mindset, to explore user needs, to pinpoint relevant consumption-related design challenges, and to identify new design opportunities to support circular consumption.

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Chapter 4
Embedding a Sustainability Focus in Packaging Development Processes

Bjorn de Koeijer, Iris Borgman, Jörg Henseler, Roland ten Klooster, and Jos de Lange

Abstract Despite packaging sustainability aspects often being embedded in companies' strategic aims, the structured implementation of such targets is limited at the operational level, where a product's commercial viability (strategic fit, business case feasibility, and a limitation of commercial risks) and development aspects (timing issues, material use, and supply chain efficiency) are prioritized over desired sustainability goals. Packaging acts not as an isolated entity but as a part of a symbiotic product-packaging combination, of which the development is the shared responsibility of stakeholders with different backgrounds and interests. With the development and design process of product-packaging combinations being a concatenation of decisions made by multidisciplinary teams in various organizations, the structured integration of sustainability-related considerations in product-packaging development can benefit from a synthesized focus on development teams' efforts, decision-making processes, stakeholder interaction and dynamics, and trade-offs. This research addresses a vision on an approach to explore, understand, and analyze this field, specifically its key characteristics that act as enablers and barriers of product-packaging sustainability. This is targeted by interactively modelling the decision-making processes of product-packaging development, both within multidisciplinary development teams, companies, and product-packaging chains, by means of a collection of interactive tools. Key within these tools is the ability to address the multidisciplinarity of stakeholders, the decision-making processes within and beyond development teams, and the proposed and realized inclusion of sustainability-related considerations, all within a framework of tacit and explicit knowledge.

The original version of this chapter was revised: The author group was incorrect. The author group "Kenichiro Chinen, Hideki Endo, Mitsutaka Matsumoto, and Yongliang Stanley Han" has been changed to "Bjorn de Koeijer, Iris Borgman, Jörg Henseler, Roland ten Klooster, and Jos de Lange" in the Frontmatter and in the Chapter. The correction to this chapter is available at https://doi.org/10.1007/978-981-15-6775-9_44

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Keywords Operational development · Strategic development · Sustainable development · Packaging development · Development team

4.1 Introduction

Attention towards sustainability- and circularity-related aspects in product-packaging development is increasing. Various targets are set, ranging from potential recyclability to the use of recycled materials and an overall reduction in packaging quantities. However, the structured implementation of such targets is often limited on the operational level. To take such aspects into account during the development process, trade-offs with other packaging features need to be made by product-packaging development teams. Even though sustainability aspects are often embedded in companies' strategic aims, the alignment of the strategic and operational levels of development shows to be limited. Therefore, design integration and inclusion of multiple stakeholders, disciplines, and perspectives shapes the core aim of this research's direction; synthesis over analysis as intervention towards improvements. This research addresses a vision on an approach to explore, understand, and analyze this field, by means of identifying the current problems and describing design research-based options for efforts to target these. This article aims to share insights which act as a foundation for this vision, with a focus on the reasoning behind synthesis-based interventions aiming to bridge the gap between academic understanding and industry challenges. We aim to enable development teams in ensuring the structured implementation of sustainability- and circularity-related considerations in product-packaging development, for which this vision paper provides a substantiation.

Within our scope, the main subject is the process of packaging development, with the synthesis of design interventions targeting the structured implementation of sustainability- and circularity-related considerations as a core aim. Following, this research's first quest is to explore this field's key characteristics, trade-offs, and boundaries that act as enablers and barriers of product-packaging sustainability and circularity. Secondly, the research focuses on adapting and improving the current situation by means of design interventions towards implementing sustainability considerations in product-packaging development processes. In the development process towards these interventions, synthesis follows analysis-focused, pattern-recognizing research steps, which renders this scope as solution-focused design research (Cross 1982; Buijs 2003; Pahl et al. 2007; Eekels and Roozenburg 1991; Swann 2002).

4.2 Point of Departure

4.2.1 Product-Packaging Sustainability

Within this research vision, we consider packaging as (a set of) physical artefacts that temporarily or unremittingly assumes the functions of preserving, protecting, enabling use and handling, and conveying formal and informal information about the related product (de Lange et al. 2013). Packaging acts as an object which is subservient to its contents, undertaking functionalities of the standalone product, in order to provide the ability to bridge time and distance from manufacturer/producer to consumer (ten Klooster 2002). Following, packaging cannot be regarded as an isolated entity, but acts as a beneficial add-on to the product, which fulfils functions during different steps of a supply chain (Motte et al. 2007; de Koeijer et al. 2017b). A product-packaging combination shapes a symbiotic, interrelated entity in a complex and multidisciplinary network of stakeholders (de Lange et al. 2013; Oude Luttikhuis et al. 2014; Molina-Besch et al. 2014). Consequently, the interlinked life cycles of both the packaging and the product must be considered during the development process (de Lange et al. 2013; ten Klooster 2002; Oude Luttikhuis et al. 2014; Bramklev 2009). It is therefore incorrect to consider the environmental impact of packaging separately from the environmental impact of the product contained within the packaging (de Koeijer et al. 2017a). The isolated consideration of packaging as a separate entity leads to suboptimal solutions—therefore, the integrated development of product and packaging is important to develop optimal product-packaging combinations (ten Klooster 2002; Bramklev 2009; Olander-Roese and Nilsson 2009). Even though the environmental aspect of a package as an isolated entity is important, the scope of sustainable development should be broader than merely optimizing certain existing aspects of the packaging design. Within any supply chain—especially when a sustainability focus plays a role—this integrated perspective is essential. Sustainable considerations should cover the impacts of the entire product-packaging combination and should be targeted at all levels of detail—from added value and functionality to product definitions and materials, and end-of-life considerations.

4.2.2 Product-Packaging Development Processes

We regard the development process of product-packaging combinations as a subsection of ‘traditional’ product development. Both are characterized by iterative processes of analysis, synthesis, simulation, and evaluation steps (Buijs 2003; Eekels and Roozenburg 1991; Swann 2002; Cross 2000).

The development of a product-packaging combination is the shared responsibility of different stakeholders with various backgrounds and interests. Consequently, the entire development and design process of a product-packaging combination is a concatenation of decisions made by multidisciplinary teams in various organizations (de Lange et al. 2013; Sheldrick and Rahimifard 2013). For this reason, the dynamics within those teams are of high value, this determines the extent to which desired sustainability aspects are expressed in the final product-packaging combination, as the result of the development process (de Koeijer et al. 2017a).

Most existing efforts regarding packaging sustainability—both in academia and industry—focus on minimizing the negative environmental impact of packaging materials, which is a blueprint eco-efficient view on the perceived superfluous nature of packaging as an isolated entity (de Koeijer et al. 2017b). This ignores the facilitator perspective of packaging as a subpart of an integrated product-packaging combination. In many cases, this materializes in late-stage optimizations, aiming for the reduction and elimination of packaging elements from supply chains. In addition, the adoption of one design strategy or key focus over another may result in trade-offs between sustainability- and circularity-related aspects, and other indicators, such as a product's commercial viability (strategic fit, business case feasibility, and a limitation of commercial risks) and development aspects (timing issues, material use, and supply chain efficiency) (de Koeijer et al. 2017a), visualized in Fig. 4.1. Strategic-level corporate packaging sustainability objectives ("desired sustainability") may influence the weighting of specific life cycle impacts and thus influence ultimate operational design strategies ["perceived and achieved sustainability" (de Koeijer et al. 2017a)]. In general, sustainable product-packaging design calls on designers to balance factors and optimize them, while keeping in mind that optimizing for one parameter may shift but not necessarily limit the negative environmental burden of the product-packaging combination.

4.2.3 Packaging Within Societal Boundaries

The increasing attention towards sustainability- and circularity-related aspects in product-packaging development can be illustrated with a number of societal trends. More and more packaging producers apply recycled content into their packaging designs or allow better separability of different packaging materials, and actively communicate about this. Producers of packed products (brand owners and co-packers) are also becoming more aware of packaging's indirect environmental impact: food waste as a result of insufficient packaging. This contrasts the direct environmental impact of packaging (expressed by the packaging material contents' environmental impact) and is therefore a sensitive subject when considering product-packaging combinations as symbiotic integrated systems.

The behaviour of consumers plays a significant role in this, both by means of 'correct' (designed) use of packaging, and by the general unbalanced view on packaging as being superfluous or excessive, by focusing on features that become apparent after purchase (de Koeijer et al. 2017b). The design of packaging influences consumer behaviour during the process of purchasing a product-packaging combination (Magnier and Crié 2015; Steenis et al. 2017), also when specifying this to the influence of perceived environmentally sound packaging elements (Rokka and

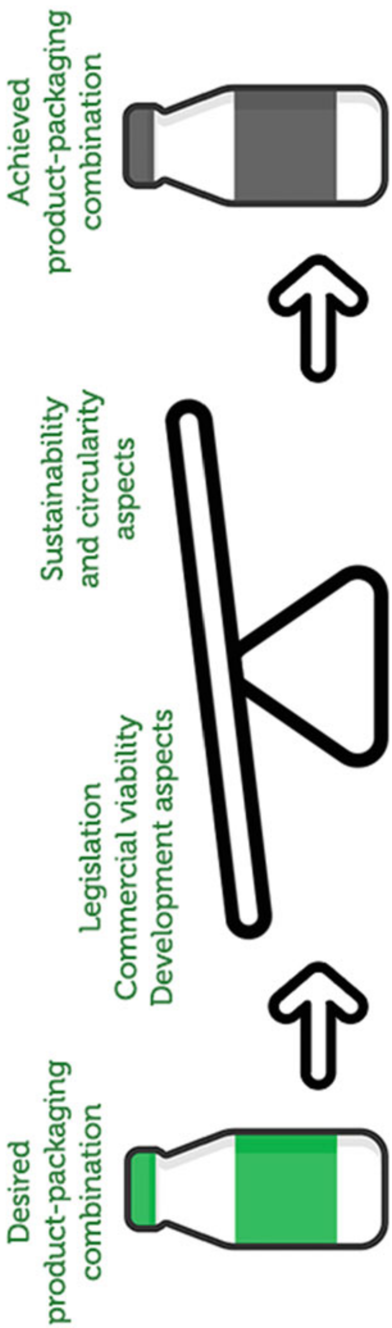

Fig. 4.1 Balancing sustainability- and circularity-related trade-offs

Uusitalo 2008; Magnier et al. 2016; Magnier and Schoormans 2015). Packaging communication, understandability, and reliability regarding environmental issues are important, even when gaps between the perceived packaging sustainability by consumers contrasts the 'measurable' packaging sustainability score (Steenis et al. 2017). Also with regard to the recycling process, packaging design plays an important role, it can be regarded as a tool to promote recycling among individuals who do not necessarily intend to engage in this behaviour (Verschoor et al. 2018). Additionally, it is important that consumers are informed how several parts of the packaging should be separated and discarded (Borgman et al. 2018). During the decision-making process which determines the product-packaging design, it is therefore of great importance to take environmentally-focused packaging features and the subsequent consumer behaviour into account.

Besides the consumer behaviour aspect, governmental regulations define a significant influencer of product-packaging sustainability. In addition to policies which target packaging waste, such as EU directives 94/62/EC (European Parliament and Council 1994) and 2015/720 (European Parliament and Council 2015), recent endeavours identify plastics as a key priority in the EU's circular economy action plan (European Commission 2018). It proposes the reduction of the impact of plastics in the environment (mainly targeting marine litter) (European Commission 2018) and in The Netherlands a ban on giveaway plastic bags (Dijksma et al. 2015). Even though these efforts are not by definition erroneous, they do address current issues in a merely eco-efficient manner, of which the appropriateness is up for debate. Next to those policies, in the Ellen MacArthur Foundation's publication 'The New Plastics Economy' (Ellen MacArthur Foundation 2016), the entire value chain of plastic packaging—in which design plays a vital role—is described as an essential element, with a direct and significant impact on the economics of collection, sorting and recycling. The choice of packaging materials, colours, formats and other design factors determines whether a package can generate positive after-use revenues if it is recycled, or if it will end up in low-grade disposal and lead to additional costs.

4.2.4 Point of Departure: Conclusion

The preceding sections explore the realm of product-packaging sustainability, which lead to a number of points that are relevant for a structured inclusion of front-end sustainability considerations, contrasting the current eco-efficient late-stage integration of sustainability- and circularity-related considerations. Design and redesign are important instruments to improve product-packaging sustainability. Even though potential design changes which are targeted at four problematic segments in plastic packaging are presented (e.g. in 'The New Plastics Economy'), there is no further indication explaining the consequences for the design process and how design teams should apply this knowledge. For multidisciplinary product-packaging development stakeholders, the decision-making processes revolve around a multitude of issues, both within and beyond the described societal boundaries. Finding a balance between these aspects and the accompanying trade-offs poses a key challenge. Therefore, the inclusion of these issues within decision-making is essential, but currently a struggle for product-packaging development teams. Structured interventions are required, especially targeting decision-making processes and stakeholder interrelations.

4.3 Research Method

Our proposed method of researching, synthesizing, and overcoming the addressed issues revolves around interactively modelling the decision-making processes of product-packaging development, within multidisciplinary development teams, companies, and product-packaging chains, in case-study settings. We apply a selection of tailor-made tools and techniques, both currently available and under (re)development, to simulate a product-packaging development process with a diverse team, including various roles with expertise on numerous subjects. Key within these tools is the ability to address the multidisciplinarity of stakeholders, the decision-making processes within and beyond development teams, and the proposed and realized inclusion of sustainability-related considerations, all within a framework of tacit and explicit knowledge. The aim of the tools is to map development processes, and to provide practical insights into the integration and inclusion of sustainability-related requirements and decisions during development processes, how this affects other requirements, and how to deal with trade-offs. We aim to form a bridge between product-packaging value proposition, and materials and processes, which must result in applicable interventions for development teams to ensure the structured implementation of sustainability- and circularity-related considerations in product-packaging development, linking desired, perceived and achieved sustainability (de Koeijer et al. 2017a).

4.3.1 Research Phases

The research is conducted by means of various (recent) product-packaging development cases, executed by industry. In each case, the cooperation between the researchers and the company is spread out over four phases:

1. *Inventory*

Defining the research cooperation, involved stakeholders/parties, and goal setting. This phase targets the overall clarification of the main focus of the research.

2. *Audit*

Mapping the current situation. This phase is executed by means of an interactive visualization tool (described in the next section), by means of which we map the design landscape (an analysis of involved stakeholders, actions, decision-making processes, and criteria), and benchmark this. The result of this phase is a timeline of the design process for a specific case, specifically targeting (potential) bottlenecks relating to the previously defined research focus.

3. *Synthesis*

Combining the collected insights, and developing these into interventions which specifically aim to reach the defined goals, related to the company's current position in the design landscape. Primary points of focus are the stakeholder interrelations and decision-making processes.

4. *Implementation*

Transitioning from theory to practice, aiming (1) to progress towards the structured implementation of sustainability- and circularity-related considerations in product-packaging development, and (2) to make these options explicit and clarify potential risks and bottlenecks related to the actual practical implementation.

The result of these phases is a collection of tools and interventions by means of which the company under consideration can accelerate the transition towards more well-defined sustainable product-packaging combinations. Within this approach, we explicitly focus on the interest of the company under consideration, in order to (co-)define the main goals and aims. This research is not targeted to 'how things must be done', but rather to assist in aligning desired and achieved sustainability; aligning the strategic and the operational level of product-packaging sustainability.

4.3.2 Tools and Techniques

In phases 2 and 4, specific tools are applied to conduct the research:

Visualization Tool (Phase 2)

The visualization tool we apply is based on the tool as described by de Koeijer et al. (2017a, b). This tool is developed to address the implicit interrelations between actors, actions, decisions, and criteria, and non-linearity and iterations in development processes—which are often difficult to grasp by means of traditional (semi-structured) interviews—and is based on a selection of cards. In three stages, the interview addresses a deeper level of stakeholder involvement: stage 1 addresses a stakeholder's main project contributions for the case under consideration, stage 2 addresses a synopsis of the project ("scenes"), stage 3 builds towards a network of interrelations, by means of the interview questions, answers, and various cards. Figure 4.2 illustrates the elements of the visualization tool in an example post-interview configuration.

In each case, we apply this visualization tool in interview sessions with individual stakeholders. This results in isolated insights in each stakeholder's perspectives on a project, of which the synthesis is the sole responsibility of the researchers, in research phase 3. The application of this visualization tool mainly results in advantages related to the active involvement of an interviewee in the interviewing process, and the

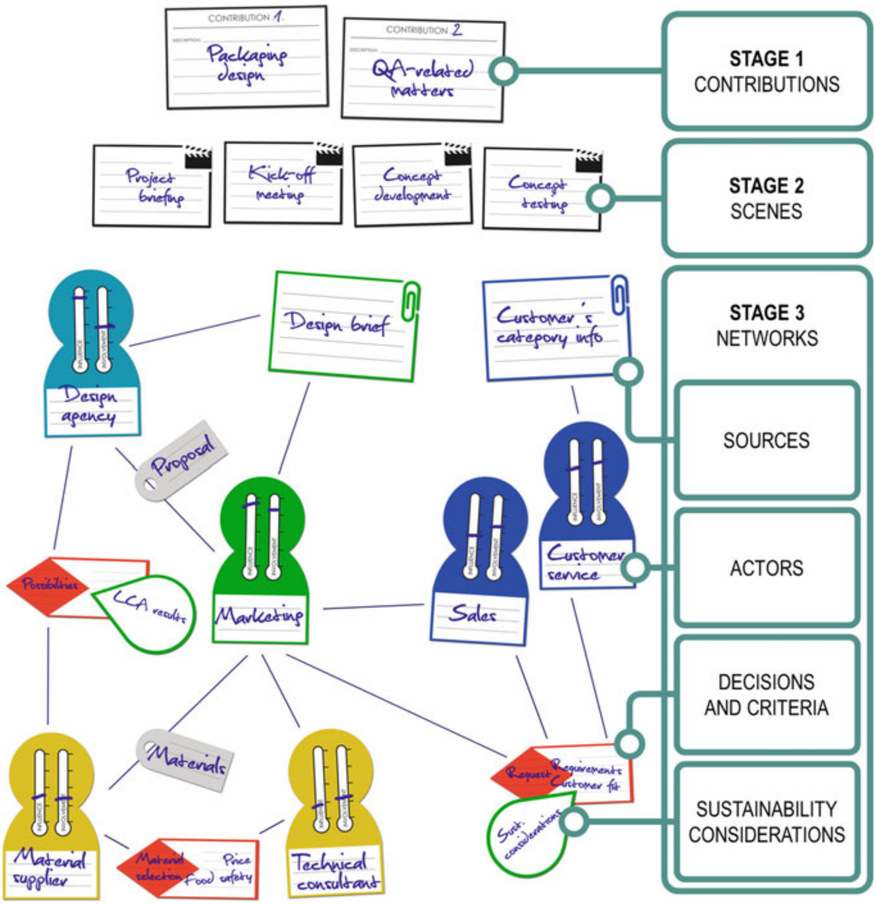

Fig. 4.2 Visualization tool elements. Adapted from de Koeijer et al. (2017a)

creation of a 'talking piece', limiting the necessity of creating a mental image and interpretation of the discussed development process by the researchers (de Koeijer et al. 2017a).

Serious Gaming Intervention (Phase 4)

The tool we plan to apply in phase 4 is a serious gaming concept, specifically focused on addressing stakeholder mapping and decision-making as an intervention towards improvements. This concept is currently subject to re-iteration and redevelopment. The game simulates a product development process executed by a multidisciplinary team and serves as a mapping model and intervention tool for those processes. The participants of the game resemble a development team existing of different stakeholders. During the game itself, participants are asked to develop a product, in sequential development steps. This involves interpreting a client's design brief, designing product concepts, and production and assembly steps (de Koeijer et al. 2016). Key within this serious gaming concept (currently addressed as 'design game') is the ability to address the combined multidisciplinarity of stakeholders in one session, the decision-making processes within and beyond development teams, and the proposed and realized inclusion of sustainability-related considerations.

4.4 Discussion and Conclusions

With a significant part of a product-packaging combination's impact determined during the design and development phase—as environmental lock-in (de Koeijer et al. 2017b)—and that phase being the shared responsibility of various stakeholders, the dynamics within those teams are highly influential to the achieved sustainability of a product-packaging combination. However, with the currently identified limited alignment of a company's strategic aims with the operational results (perceived and achieved sustainability), further efforts are required to target this in a more structured way. By means of this research effort, we aim to provide the industry with interventions targeting stakeholder interrelations and decision-making processes, with development team dynamics and role divisions as key points of focus. With the aid of the visualization tool and design game, we can provide the packaging industry with more solid insights into their own development processes, and determine the adjustments required to further structurally implement sustainability- and circularity-related aspects. We explicitly do not aim to prescribe 'what must be done' in the realm of packaging sustainability, but rather aim to assist in aligning strategic targets and aims with operational development efforts.

This article not only acts as a vision on our exploration approach in this field, but it is also a call for action. We hope that this vision paper calls out to academic partners willing to further explore this field and its options for interventions, together with us (CRiSP, the Center for Research in Sustainable Packaging), to accelerate the structured integration of sustainability-and circularity-related considerations in the development processes of a key element of nowadays society: product-packaging combinations.

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Chapter 5
Consumer's Perception of Plastics in Everyday Products in Relation to Their Personality

Lore Veelaert, Els Du Bois, Laure Herweyers, and Ingrid Moons

Abstract In order to contribute to a circular economy, as designers, we can aim to assure an extended product lifetime, which can be done following a strategy of creating product attachment. From a consumer perspective, people tend to identify themselves with the products they (want to) own and use, reflecting their identities, who they are and how they see themselves. Thus, product attachment can be positively affected by the congruity with one's personality. A successful product needs to fulfil the user's needs, create meaningful experiences and evoke emotions to survive in the competitive market, which also counts for the materials that the product is made of. These materials can be considered from both a technical engineering (production, durability, waste, etc.) and a user-centred experiential perspective (material perception). Therefore, this qualitative research aims to explore the consumers' perception of plastic materials in everyday products and its link with their own personality. The paper describes the results of a mobile survey in which respondents (n = 195, average age of 29 years) were asked to upload a picture of their most and least favourite, plastic product that they use in everyday life, to describe the material(s) it is made of and explain why it (does not) fit with their personality. By means of content analysis, a categorization was made of the uploaded products and the various characteristics that described the materials and attributed to the personality fit, and a cluster analysis was done to create four personality clusters of consumers and their associated material descriptions. We suggest that insights in the relationship between the consumer's personality and his/her material preference will

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support designers in choosing appropriate materials to create desirable products with a prolonged life-time.

Keywords Material perception · Plastics · Personality · Product attachment · Product life time

5.1 Introduction

Within a circular economy, one way to extend the life-time of products is by simply using a product for a longer time (Ellen MacArthur Foundation, McKinsey & Company 2012). Creating product attachment is one strategy to attain such a prolonged product use (Bakker and Schuit 2017; Mugge et al. 2005). Product attachment is defined as "the emotional bond a consumer experiences with a product" (Mugge et al. 2005; Schifferstein and Zwartkruis-Pelgrim 2008) and can be positively affected by the congruity with a person's personality. A successful product needs to fulfil the user's needs, create meaningful experiences and evoke emotions in order to survive in the competitive market (Karana et al. 2014). In addition to a product's form or brand, the perception of the user is also influenced by the materials that a product is made of and the resulting materials experience. Hence, a product's material that enhances an emotional bond and suits the user's personality, can also attribute to longer product use (Mugge et al. 2005; Norman 2004).

Today, materials are a substantial aspect of sustainable design in a circular economy. However, materials can be regarded from both a technical engineering (production, durability, waste, etc.) and a user-centred experiential perspective (Van Kesteren 2010; Karana et al. 2010). From a material perspective, various experiential levels can attribute to a material's expression, and the most well-known levels are defined by Camere and Karana (2017) as sensorial attributes (e.g. gloss, texture, colour), associative (e.g. cheap, male, nostalgic), emotional (e.g. surprising, boring), and performative (e.g. stroking, folding). However, no one-to-one correspondence can be found between these expressive values and a certain material, as a material's perception is influenced by product, user and context related factors, making this subjective topic rather complex to study (Van Kesteren 2010; Karana et al. 2010; Karana 2010).

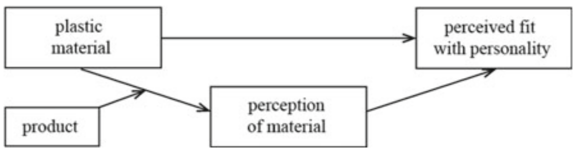
From a consumer perspective, people tend to identify themselves with the products they (want to) own and use (Zuo 2010; Choi 2017), they reflect their identities, who they are and how they see themselves (Govers 2004; Belk 1988). The preference of a consumer for a particular product, and the materials it is made of, is influenced by the fit or consistency with the self of the consumer (Sirgy 2015; Hosany and Martin 2012). This expression of the self can be described by attitudes, beliefs, norms, values or traits. Regarding the latter, personality traits are considered universally across diverse cultural and age groups and "describe what people are like, rather than what people consider important" (Schwartz 2012) (i.e. thoughts, feelings, actions). Throughout one's lifetime, these traits can occur in varying frequency and intensity. The most widely accepted personality traits are the "Big Five" dimensions or the Five-Factor Model of Costa and McCrae (1987), Brunel and Kumar (2007), Openness, Conscientiousness, Extraversion, Agreeableness, and Neuroticism. In addition, relationships between products and personalities (and thus, materials) have been found as well, and are translated into everyday personality adjectives by Govers (2004), Mugge et al. (2009). Finally, Aaker (1997) extended the Big Five structure to brand personality, including socio-demographic aspects such as gender and social class, which was adapted by Geuens et al. (2009) to a new and cross-cultural validated brand personality measure that is easy to comprehend: Responsibility, Activity, Aggressiveness, Simplicity, and Emotionality.

From a product perspective, a critical market is that of Fast Moving Consumer Goods (FMCG) and other everyday consumer products that are sold rather quickly and at a relative low cost, and are most often materialized by plastics (Çelen et al. 2005). The perception of plastics materials has known a changing path, as it was introduced as an imitation material in the '50, then re-valued as a versatile material thanks to Tupperware (Manzini 1986), but is nowadays regarded as the cause for many environmental issues such as the plastic soup. However, plastics can still offer valuable sustainable opportunities, when used smartly and correctly, i.e. when a designer can create product life extension through meaningful materials experience.

5.2 Research Aim

In this paper, we aim to explore possible relationships between (plastic) materials, found in everyday products, their expressive value and the link with the personality of the consumer, whereby personality in this research is defined in terms of the five brand personality traits (Geuens et al. 2009). Figure 5.1 visualises the reasoning model that involves everyday products as moderator of the perception of a plastic material, which mediates the perceived fit of the plastic with the consumer's personality. The following research question can be formulated: "*How does the consumer's personality influence the perception of a material and the perceived fit with the personality?*". Based on new insights on how consumers describe materials in relation to their personality, this qualitative exploratory research intends to provide guidance for future quantitative research on materials from the perspective of consumer personality segmentation.

Fig. 5.1 Reasoning model



5.3 Methodology

5.3.1 Procedure

In order to provide an answer to the proposed research question, a mobile survey was prepared to collect the required data on material perception and consumer personality. This mobile survey consisted of two parts. First, members of the consumer panel were invited to participate in the first part through their account on the mobile survey application. They were shown a short introductory movie with subtitles that introduced them to the amount of materials of the products that we see and touch in our daily life. Afterwards they were asked to prepare themselves for the second part by looking for daily consumer products made in (hard) plastic materials that would either fit—or not fit at all—with their personality.

Second, respondents were asked to upload a picture or photograph of a plastic product that they use in everyday life that fits with their personality and self-identity. In addition, in two open ended questions, they were asked to describe the material(s) it is made of and explain why it fits with their self. This was repeated for a product that did not fit at all with their personality.

Third, respondents were asked to score five brand personality items on a five-point Likert scale, based on Aaker (1997), Geuens et al. (2009): Responsibility, Activity, Aggressiveness, Simplicity, Emotionality.

5.3.2 Respondents

195 respondents participated in a mobile survey that was conducted in collaboration with a consumer panel company. The average age of the respondents was 29 years ($\sigma = 10$), ranging from 16 to 61 years, and 106 respondents were male, 73 were female and 16 undefined. Regarding the validity of the respondent's submissions, depending on the question, at least 173 valid inputs were recorded.

5.3.3 Processing

Demographic data such as gender and age were collected in an Excel file through the consumer panel database and were used for descriptive analysis. This data was complemented with the uploaded pictures, the descriptions of the respondents, and their scores on the brand personality scales.

Next, a content analysis (Erlingsson and Brysiewicz 2017) was chosen as a flexible method to analyse text-based results, and to transform qualitative data into more quantifiable data. A group of five design researchers determined a set of categories based on the overall answers for both the material descriptions and fit descriptions, largely based on categories commonly found in literature (Camere and Karana 2017; Karana et al. 2008). Next, each researcher individually assessed each respondent's answer—divided into separate sub-answers—and coded which categories that were applicable to each (sub) answer. Afterwards, possible disagreements were discussed in group to finalize the categorization and allow frequency count. Table 5.1 gives an overview of the categories, their descriptions and some examples that were found in the data.

Furthermore, by means of a similar procedure, all uploaded pictures were assessed to appoint the displayed products and to count their frequencies. For increased comprehensibility, these products were summarized in several product categories, as shown in Table 5.2, complemented with product examples from the data.

Table 5.1 Descriptive categories derived from results of material description and fit description

Descriptive category	Material description	Fit description	Explanation	Examples
Sensorial	X	X	Vision, sound, touch, etc.	Warm, soft, light, flexible, glossy
Associative	X	X	Meanings, interpretations	Cheap, clean, robust, nostalgic
Ecological	X	X	Sustainable characteristics	Durable, reusable, recycled
Functional	X	X	Usability and utilitarian aspects	Handy, versatile, user friendly
Personality	X	X	Human traits	Friendly, sincere, cheerful, vain
Shape	X		Form-related characteristics	Rounded, sharp-edged, square
Habit/interest		X	Habitual and interest aspects	Fun for me, don't like, use a lot

Table 5.2 Examples within product categories

Consumables	Plastic bag, bottle, can, packaging, straw, shampoo bottle
Kitchen utensils	Bread box, water bottle, oven mitt, coffee machine, soap dispenser
Electronics	Computer, remote, headphone, vacuum cleaner, power bank
Office	Pen, paper cutter, calculator
Interior	Chair, doorknob, light switch, lamp, table
Personal/fashion	Shoe, glasses, watch, backpack
Toys	Dice, Playmobil
Transport	Car steering, handlebar, helmet
Garden	Flowerpot, watering can
Other	3D print, car key, CD, artwork

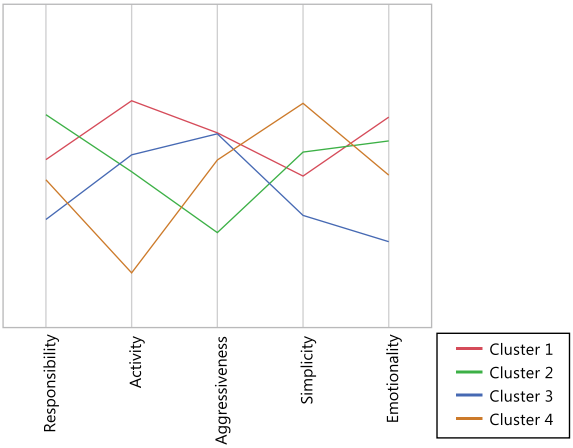


Fig. 5.2 Cluster means diagram

Finally, the respondent's scores on the five brand personality traits were used in a cluster analysis to create consumer segments that can be built upon in further analysis. Based on an outlier assessment, five respondents were discarded as they did not score the personality items, leading to 190 valid data inputs that were used.

5.4 Results

5.4.1 Cluster Analysis

A hierarchical cluster analysis was performed on the five brand personality traits. Four clusters of a similar size were identified, and their cluster means on the personality traits are shown in Fig. 5.2. Based on the analysis of the material and personality fit descriptions, these clusters will be further detailed throughout the next sections.

5.4.2 Descriptive Categories

The results of the two open-ended questions for a positive and negative fit with the personality were processed into descriptive categories by means of content analysis. Table 5.3 shows the frequencies of descriptions within each category for all four questions.

First of all, this frequency table shows that the material description questions delivered more (partial) descriptions compared to the fit questions, which could reflect the fact that they were easier to elaborate on. Overall, the categories of Sensorial, Associative, Ecological and Personality descriptions were most common.

Table 5.3 Frequencies and relative counts of descriptive categories for materials and fit within the four clusters

		Cluster	Sensorial		Associative		Ecological		Functionality		Personality		Shape		Habit/interest		Total per cluster		Total
			N	R%	N	R%	N	R%	N	R%	N	R%	N	R%	N	R%	N	%	
Positive fit	Material description	**C1**	50	47.6	29	27.6	7	6.7	11	10.5	7	6.7	1	1.0	–	–	105	25.4	**413**
		C2	96	67.1	22	15.4	9	6.3	10	7.0	3	2.1	3	2.1	–	–	143	34.6	
		C3	55	60.4	21	23.1	4	4.4	4	4.4	6	6.6	1	1.1	–	–	91	22.0	
		C4	53	71.6	7	9.5	4	5.4	5	6.8	2	2.7	3	4.1	–	–	74	17.9	
		T	254	61.5	79	19.1	24	5.8	30	7.3	18	4.4	8	1.9	–	–			
	Fit description	**C1**	7	10.3	13	19.1	14	20.6	8	11.8	19	27.9	–	–	7	10.3	68	27.6	**246**
		C2	15	19.2	14	17.9	12	15.4	9	11.5	22	28.2	–	–	6	7.7	78	31.7	
		C3	12	20.7	17	29.3	6	10.3	5	8.6	14	24.1	–	–	4	6.9	58	23.6	
		C4	9	21.4	6	14.3	8	19.0	7	16.7	8	19.0	–	–	4	9.5	42	17.1	
		T	43	17.5	50	20.3	40	16.3	29	11.8	63	25.6	–	–	21	8.5			
Negative fit	Material description	**C1**	61	56.0	33	30.3	9	8.3	5	4.6	1	0.9	0	0.0	–	–	109	29.2	**373**
		C2	47	41.2	45	39.5	14	12.3	5	4.4	2	1.8	1	0.9	–	–	114	30.6	
		C3	43	56.6	22	28.9	6	7.9	2	2.6	1	1.3	2	2.6	–	–	76	20.4	
		C4	52	70.3	12	16.2	6	8.1	0	0.0	1	1.4	3	4.1	–	–	74	19.8	
		T	203	54.4	112	30.0	35	9.4	12	3.2	5	1.3	6	1.6	–	–			
	Fit description	**C1**	22	27.8	18	22.8	15	19.0	1	1.3	16	20.3	–	–	7	8.9	79	30.6	**258**
		C2	12	15.4	22	28.2	22	28.2	5	6.4	14	17.9	–	–	3	3.8	78	30.2	
		C3	10	17.9	15	26.8	13	23.2	0	0.0	16	28.6	–	–	2	3.6	56	21.7	
		C4	7	15.6	8	17.8	15	33.3	2	4.4	8	17.8	–	–	5	11.1	45	17.4	
		T	51	19.8	63	24.4	65	25.2	8	3.1	54	20.9	–	–	17	6.6			
Total		**C1**	**140**	**38.8**	**93**	**25.8**	**45**	**12.5**	**25**	**6.9**	**43**	**11.9**	**1**	**0.3**	**14**	**3.9**	**336**		**1290**

(continued)

Table 5.3 (continued)

	Cluster	Sensorial		Associative		Ecological		Functionality		Personality		Shape		Habit/interest		Total per cluster		Total
		N	R%	N	R%	N	R%	N	R%	N	R%	N	R%	N	R%	N	%	
	C2	**170**	**41.2**	**103**	**24.9**	**57**	**13.8**	**29**	**7.0**	**41**	**9.9**	**4**	**1.0**	**9**	**2.2**	**413**		
	C3	**120**	**42.7**	**75**	**26.7**	**29**	**10.3**	**11**	**3.9**	**37**	**13.2**	**3**	**1.1**	**6**	**2.1**	**281**		
	C4	**121**	**51.5**	**33**	**14.0**	**33**	**14.0**	**14**	**6.0**	**19**	**8.1**	**6**	**2.6**	**9**	**3.8**	**235**		

Next, the two experiential levels (Sensorial and Associative descriptions) were most common when describing the materials of the chosen products. However, in case of the fit description questions, more Ecological descriptions appeared, as well as Personality descriptions, which was expected.

However, Ecological characteristics were cited more in the context of the negative fit question (e.g. not recyclable, not reusable, disposable, waste, etc.), whereas in the context of a positive fit, it was more related to their personality or values (e.g. I try to live sustainably). As the focus of this survey was on products materialized in plastic materials, the descriptions related to ecology surfaced spontaneously, which could fit within the current social debate.

5.4.3 Product Categories

Similar to the previous procedure, the uploaded pictures of plastic products were assessed visually and appointed to one of ten product categories in order to facilitate a comprehensive overview and to count the occurring frequencies. A typical product category that could be expected in the context of plastic materials, is that of Consumables which often contain single use plastics.

Several types of products were uploaded by different respondents. For example, regarding a positive personality fit, 13% of the respondents chose a re-usable water bottle, 6% a bread box, 4% a smartphone cover, computer or tv remote, and 3% a cup or flowerpot. By contrast, regarding a negative personality fit, 11% of the respondents chose a plastic bag or a bottle, 7% packaging, 4% a bread box or pot, and 3% a cup or a storage box.

Between the four clusters, small differences were detected on the top two of chosen products, however, the re-usable water bottle and bread box were most popular for a positive fit, as well as the plastic bag and bottle for a negative fit.

Table 5.4 depicts the counts of uploaded products within each product category and within a positive or negative fit with the personality. Overall, the three first categories in the table were uploaded most often. The greatest difference between a positive and negative fit could be found within the product category of Consumables that were most often negatively associated with the self. In addition, Electronics, Kitchen Utensils and Personal/Fashion items were found more within a positive fit compared to a negative fit.

5.4.4 Descriptive Categories × Product Categories

In order to gain more insights in the relation between Material and Fit descriptions, the relative count of each description category (e.g. Sensorial) within each product category was calculated for both the positive fit (Table 5.5) and the negative fit (Table 5.6).

Table 5.4 Frequencies and relative counts of the product categories for a positive and negative fit within the four clusters

Product category	Positive fit										Negative fit									
	C1		C2		C3		C4		Total		C1		C2		C3		C4		Total	
	N	C%	N	C%	N	C%	N	C%	N	C%	N	C%	N	C%	N	C%	N	C%	N	C%
Consumables	5	9.8	3	5.9	4	8.5	3	8.8	**15**	**8.2**	15	30.6	24	49.0	9	22.0	10	33.3	**58**	**34.3**
Kitchen utens.	17	33.3	13	25.5	12	25.5	10	29.4	**52**	**28.4**	8	16.3	7	14.3	13	31.7	10	33.3	**38**	**22.5**
Electronics	9	17.6	13	25,5	8	17.0	11	32.4	**41**	**22.4**	6	12.2	6	12.2	1	2.4	2	6.7	**15**	**8.9**
Office	4	7.8	1	2.0	1	2.1	2	5.9	**8**	**4.4**	3	6.1	3	6.1	1	2.4	5	16.7	**12**	**7.1**
Interior	4	7.8	2	3.9	2	4.3	3	8.8	**11**	**6.0**	6	12.2	1	2.0	3	7.3	0	0	**10**	**5.9**
Pers./fashion	4	7.8	6	11.8	6	12.8	2	5.9	**18**	**9.8**	4	8.2	2	4.1	1	2.4	1	3.3	**8**	**4.7**
Toys	0	0	2	3.9	2	4.3	1	2.9	**5**	**2.7**	1	2.0	1	2.0	1	2.4	0	0	**3**	**1.8**
Transport	1	2.0	2	3.9	1	2.1	0	0	**4**	**2.2**	0	0	0	0	0	0	0	0	**0**	**0.0**
Garden	0	0	2	3.9	4	8.5	0	0	**6**	**3.3**	0	0	0	0	0	0	0	0	**0**	**0.0**
Other	7	13.7	7	13.7	7	14.9	2	5.9	**23**	**12.6**	6	12.2	5	10.2	12	29.3	2	6.7	**25**	**14.8**
Total counts	**51**		**51**		**47**		**34**		**183**		**49**		**49**		**41**		**30**		**169**	

Table 5.5 Relative count of description categories per product category within a positive fit

Product category	Material description							Fit description						
	Sensorial (%)	Associative (%)	Ecological (%)	Functionality (%)	Personality (%)	Shape (%)	Total (%)	Sensorial (%)	Associative (%)	Ecological (%)	Functionality (%)	Personality (%)	Habit/interest (%)	Total (%)
Consumables	61	4	9	17	4	4	**100**	7	7	7	0	50	29	**100**
Kitchen utensils	57	17	16	7	1	2	**100**	23	9	36	18	10	4	**100**
Electronics	68	16	0	8	6	2	**100**	27	12	8	13	29	12	**100**
Office	68	21	5	0	0	5	**100**	33	50	0	0	8	8	**100**
Interior	46	38	0	8	8	0	**100**	6	35	0	24	35	0	**100**
Personal/fashion	55	32	3	8	3	0	**100**	10	19	10	5	52	5	**100**
Toys	78	0	0	6	11	6	**100**	20	0	0	40	20	20	**100**
Transport	57	29	0	7	7	0	**100**	29	57	0	0	14	0	**100**
Garden	63	31	0	0	6	0	**100**	0	33	17	0	17	33	**100**
Other	68	14	4	7	5	2	**100**	3	38	17	3	34	3	**100**
Total counts	**255**	**77**	**25**	**30**	**17**	**8**	**412**	**44**	**47**	**41**	**29**	**61**	**19**	**241**

Table 5.6 Relative count of description categories per product category within a negative fit

Product category	Material description							Fit description						
	Sensorial (%)	Associative (%)	Ecological (%)	Functionality (%)	Personality (%)	Shape (%)	**Total (%)**	Sensorial (%)	Associative (%)	Ecological (%)	Functionality (%)	Personality (%)	Habit/interest (%)	**Total (%)**
Consumables	50	27	19	3	1	1	**100**	11	17	48	2	20	2	**100**
Kitchen utensils	51	35	10	3	0	1	**100**	7	29	31	2	24	7	**100**
Electronics	50	44	0	0	3	3	**100**	42	17	4	4	17	17	**100**
Office	83	3	0	7	0	7	**100**	35	18	18	0	24	6	**100**
Interior	65	18	0	6	6	6	**100**	33	27	7	7	27	0	**100**
Personal/Fashion	62	33	0	5	0	0	**100**	25	50	0	8	8	8	**100**
Toys	33	33	0	33	0	0	**100**	20	40	0	0	0	40	**100**
Other	83	8	7	1	1	1	**100**	0	31	31	13	5	21	**100**
Total counts	**430**	**109**	**51**	**13**	**5**	**8**	**616**	**37**	**57**	**70**	**11**	**42**	**21**	**238**

Positive Fit

When describing materials that fit their personality, respondents tend to refer in more than half of the times to sensorial attributes such as gloss, colour, flexibility, etc., but also with associative characteristics such as robust, high-quality, cheap, etc. In contrast, when describing the reason for a material's fit with the self, the distribution over the different descriptive categories is more even, with upmost attributes referring to personality characteristics, followed by associative, sensorial and ecological characteristics.

When taking a closer look at the different product categories, Consumables were mostly described with sensorial and functionality descriptions, and their fit with personality and habit/interest descriptions. Kitchen utensils and their fit were mostly described with sensorial, associative (not fit) and ecological descriptions. Electronics and Office items and their fit were mostly described with sensorial and associative descriptions, although the former's fit was described with personality instead of associative descriptions. Interior and Personal/Fashion items were described with sensorial and associative descriptions, whereas the fit of the former was described with associative, personality and functionality descriptions, and that of the latter with personality descriptions.

Regarding the descriptive categories specifically, Sensorial descriptions were found most for Electronics, Office and the Office fit. Associative descriptions occurred mainly for Interior and Personal/Fashion products, and the fit of Office products. Ecological descriptions were used most in the case of Kitchen utensils and their fit. Functionality descriptions were found primarily for Consumables and the fit of Interior products. Finally, personality descriptions were used approximately half of the times for the fit description of Consumables and Personal/Fashion. The latter could be expected as such products are cherished and closely linked to the identity of people.

Negative Fit

When describing materials that do not fit with their personality, in two third of the cases respondents refer again to sensorial attributes, followed by associative and ecological characteristics. In contrast, when describing the fit reason, the descriptive categories are again more evenly distributed, with a focus on ecological, associative and personality characteristics. It is striking that ecological aspects are—spontaneously—often considered in the context of materials that do not suit one's personality.

All product categories were mainly described with sensorial characteristics, but also with associative descriptions in the case of Consumables, Kitchen utensils, and Electronics. The fit of Consumables was mostly described with ecological descriptions, the fit of Kitchen utensils with ecological, associative and personality descriptions, the fit of Electronics with sensorial descriptions, the fit of Office products with sensorial and personality descriptions, the fit of Interior products with sensorial, associative and personality descriptions, and finally the fit with Personal/Fashion items with associative descriptions.

Regarding the descriptive categories specifically, sensorial descriptions were found most for Office products and the fit of Electronics. Associative descriptions occurred mainly for Electronics and the fit of Personal/Fashion items. Ecological descriptions were used primarily for Consumables and their personality fit. Personality descriptions were found most for the fit of Interior products.

5.4.5 Positive Versus Negative Fit

The greatest increase or decrease of material descriptions between a positive and a negative fit could be found in the case of Toys and sensorial and associative attributes, is was a rather small product category. More differences could be found in the fit descriptions concerning the personality characteristics that were attributed to Consumables and Personal/Fashion products, concerning the ecological properties of Consumables, concerning the functionality characteristics of Toys, and finally concerning the associative characteristics of Office, Personal/Fashion products and Toys.

5.4.6 Link to Personality Clusters

Based on the obtained information of the previous Sections, the four personality clusters could be further detailed and described.

*Cluster 1—**Active** Functionalists*

Respondents within Cluster 1 are **active** and emotional personalities that focus mainly on **functionality** aspects of materials in relation to themselves, as well as associative characteristics. Cluster 1 represents a rather **young** target group (mean age = 25 years) with a 59/41 ratio of male/female. Regarding plastic materials in products that reflect their personality, they refer to Consumables and functional products in a Kitchen or Office environment, such as a re-usable bottle (17%) and a bread box (4%), whereas in case of a negative fit, Electronics, Interior and Personal/Fashion items are mentioned.

*Cluster 2—**Responsible** Ecologists*

Respondents within Cluster 2 are **responsible** and emotional personalities that focus mainly on **ecological** and associative aspects of materials in relation to themselves, supplemented with a few personality descriptions. Cluster 2 is the only cluster with a majority of **females** (55%) and its mean age is 31 years. Regarding plastic materials in products that do not reflect their personality, they clearly refer to non-sustainable and disposable Consumables and to Electronics, while Kitchen products suit their personality better, such as a re-usable bottle (15%), a bread box (4%), but also a smartphone cover (6%). Cluster 2 respondents dislike disposable plastic bags (13%) and bottles (11%).

*Cluster 3—**Personality**-Oriented People*

Respondents within Cluster 3 are active but have a predominantly **aggressive** personality and focus mainly on **personality** and **associative** aspects of materials in relation to themselves. Cluster 3 consists mainly of **men** (77%) and is mean age is 29 years. Regarding plastic materials in products that reflect their personality, they refer to Personal/Fashion items and Kitchen utensils, such as a re-usable bottle (10%), a bread box (6%) and a flower pot (8%).

*Cluster 4—Rational and Hands-On **Simplists***

Respondents within Cluster 4 appreciate **simplicity** and little activity. They are rational and hands-on and describe materials in relation to themselves with tangible **sensorial** characteristics, **shape** and habit aspects. When describing their positive or negative fit, they also mention ecological descriptions. Cluster 4 has a rather equal gender distribution (53/47 male/female) and a mean age of 31 years. Regarding plastic materials in products that reflect their personality, they refer to practical Kitchen utensils, Electronics and Interior items, such as a bread box (11%) and a re-usable bottle (9%), whereas in case of a negative fit, disposable bottles (14%) and plastic bags (9%) are mentioned.

5.5 Discussion

The presented research aimed to explore possible relationships between (plastic) materials, their expressive value and the link with the personality of the consumer, whereby personality in this research was defined in terms of the five brand personality traits. However, these five traits might be too limited for a meaningful cluster analysis as they are derived from a more extensive set of personality traits. Building upon the frequent ecological descriptions that emerged in this survey, additional segmentation items could be added to include sustainable behaviour, such as items of the NEP scale as a benchmark for pro-environmental attitudes (Anderson 2012), in order to create a more elaborate cluster analysis.

Regarding the survey methodology, a collaboration was set-up with a mobile survey company that provided fast access to respondents through their mobile app. Therefore, the context or environment in which a respondent is using the app might influence their responses. The effect of this environment has been toned down by first notifying the respondents of the interview and telling them by means of a video to get ready and look for a suitable product. Even with this measure, still a lot of the received products seem to be related to their desk or a break, places where a many of the users use the app. This might also explain the high frequency of uploaded products such as a bread box (lunch break), tv remote (near sofa) or computer mouse (office environment).

This exploration has shown some interesting opportunities for further research. Material descriptions consisted mainly of sensorial, associative and ecological characteristics, while fit descriptions included personality traits, ecological, sensorial and associative characteristics. Therefore, these four descriptive categories might offer an interesting base for next studies, using the four product categories that occurred most often (i.e. Consumables, Kitchen utensils, Electronics and Personal/Fashion items) as concrete cases in the experimental setup. In this context, specific products such as the bread box, re-usable bottle, smartphone cover or flower pot could also be further explored.

5.6 Conclusion

In a circular economy, one of the strategies to extend a product's lifetime is by creating product attachment, which can be positively affected by the congruity with one's personality. As materials are one of the building blocks of products, this qualitative exploratory research investigated the material perception of plastic everyday consumer products, and the link with the fit with the personality of the consumer.

The main output of this research resulted in four consumer clusters based on their personality and their material (fit) descriptions: (i) a younger cluster that is active and emotional and focusses on functionality, (ii) a predominantly female cluster that are responsible ecologists, (iii) a predominantly male cluster that is rather aggressive and focusses on personality and associations, and (iv) a simple and rational cluster that uses hands-on sensorial and shape-related descriptions.

Overall, sensorial, associative, personality and ecological characteristics are used most commonly in describing materials and their fit with one's personality. In addition, frequent product categories are Consumables, Kitchen utensils and Electronics, with a high occurrence of re-usable drinking bottles and bread boxes, that could be interesting product cases for further studies.

Conclusively, based on these new insights on how consumers describe materials in relation to their personality, this paper provides guidance for future quantitative research on materials from the perspective of consumer personality segmentation.

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Chapter 6
User Activity Matters: An Activity Theory Informed Design Toolkit for Sustainable Behavior Design

Wanjun Chu, Wiktoria Glad, and Renee Wever

Abstract Recent developments in eco-design have shown a growing interest in incorporating user perspectives in sustainable product and service design. However, users' needs and behavior are not static, but under a dynamic transition process. Design purely informed by user needs thus may lead to environmental and social sustainability issues. In this paper, we approach this sustainable design challenge from an activity theoretical perspective. First, we conducted a literature review on the use of activity theory (AT) in sustainable design-related studies. Based on the literature insights, we translated the abstract AT concepts into more descriptive and practical design implications. Following that, we developed an activity-centered design (ACD) toolkit prototype to support design practitioners in integrating users' dynamic activities with specific sustainable design goals in the early-stage design ideation process. Finally, we evaluated the practical use of the toolkit with both design experts and participants without a design background in a case study. Results indicated that the ACD toolkit prototype allowed participants to engage with complex sustainability issues while taking multiple aspects of users' activity into account. It also offered an interactive way for designers to better develop early-stage design ideas to solve sustainability-related problems from a product and service design perspective.

Keywords Design for sustainable behavior · Activity theory · Activity-centered design · Design ideation tool · Circular design

6.1 Introduction

Recent developments in the field of eco-design have shown a growing interest in incorporating product usage phase and user behavior in the design of sustainable

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products and services. Over the past decade, design for sustainable behavior has become a significant constituent of the social perspective in circular consumption and eco-design (Wever 2012). With the specific goal to help design practitioners to better support users in performing desired environmentally sustainable behavior, various design tools and methods, such as Design with Intent Method (Lockton et al. 2010) and Behavior Change Design Sprints (Colusso et al. 2018) have been developed and evaluated by researchers from the design for sustainable behavior and circular design field.

However, one major challenge which has been neglected in the development process of these tools is that the user-product/service interaction models and users' corresponding behaviors are not static. Rather, they are under a constant dynamic development and transition process. Furthermore, as today's products are often product–service combinations, function in networks with other products and other people (Wever et al. 2008), users' doings (the term doings here refers to behaviors, habits, and practices) can, to a large extent, be influenced by changes within the physical environment, socio-cultural background, and the presence of other available products and services (Chu et al. 2018).

The lack of consideration of the dynamic users' needs and behaviors has already become a significant contributor to the problem of rapid obsolescence (Kaptelinin and Nardi 2012) and rebound effects (Hilty et al. 2011). In other words, a product or service which aims to influence users' environmental and social behavior towards a more sustainable direction at a specific point in time does not always necessarily lead to a sustainable outcome in a long run. To address this particular challenge, we believe what is currently lacking is a design-focused theoretical perspective that incorporates the understanding of the interaction between users and products/services with users' long-term and dynamic behavior into the sustainable behavior and circular design process (Kaptelinin and Nardi 2012; DiSalvo et al. 2010).

In recent design research practices, the activity-centered design (ACD) approach and its theoretical foundation—activity theory (AT), have been applied as a promising way to inform sustainable design implications in transformative design studies (Kaptelinin and Nardi 2012). What distinguishes AT from most of other dominant social or psychology theories is its particular focus on the changing nature of human activity systems and the role that artefacts (and consequently, the design of the artefacts) play in such dynamic systems (Kuutti 2011). Drawing on this theoretical focus, ACD offers a unique perspective that informs how user activities can be mediated, changed, retained, and transformed by designed artefacts used in both individuals' daily life and the broader cultural-historical context (Kaptelinin and Nardi 2006; Norman 2005).

However, despite the fact that AT & ACD has been used in a wide range of design studies to guide design interventions, due to its rich but complex theoretical nature in social and phycological disciplines, it provides little support for design practitioners to apply this lens in their actual design practices, especially for the design explorations of sustainability issues (Williams 2009; Li and Landay 2008; Duignan et al. 2006).

In this ongoing study, we aim to explore the practical insights and implications that an activity theoretical lens can offer for sustainable behavior design. In this paper, we report on the initial development and evaluation of the AT-informed design ideation toolkit—sustainable ACD toolkit, which aims to enable designers to integrate the understandings of users' dynamic activities with specific sustainable design goals in the early-stage design ideation process.

6.2 Activity Theoretical Background

Activity theory was first proposed by Leontiev with an origin in psychology (Leont'ev 1978). AT views the human activity as purposeful need-based interaction between the subject (actor) and the object (world) (Leont'ev 2011; Vygotsky 1978). Unlike traditional psychological theories which aim at providing means to predict subjects' behavior and habits, AT is descriptive in its theoretical nature and focuses on understanding why and how people carry out a specific activity in a specific context to achieve a specific goal (Nardi 1996) (as illustrated in Fig. 6.1). Although different AT models have been developed by Leont'ev (1978), and Vygotsky (1978), and Engeström (2014) with different analytical emphasis, they all incorporate the six theoretical concepts: (1) Mediating tools, (2) Historical development, (3) Sociocultural contexts, (4) Tensions and contradictions. (5) Motivations, goals, and outcomes,

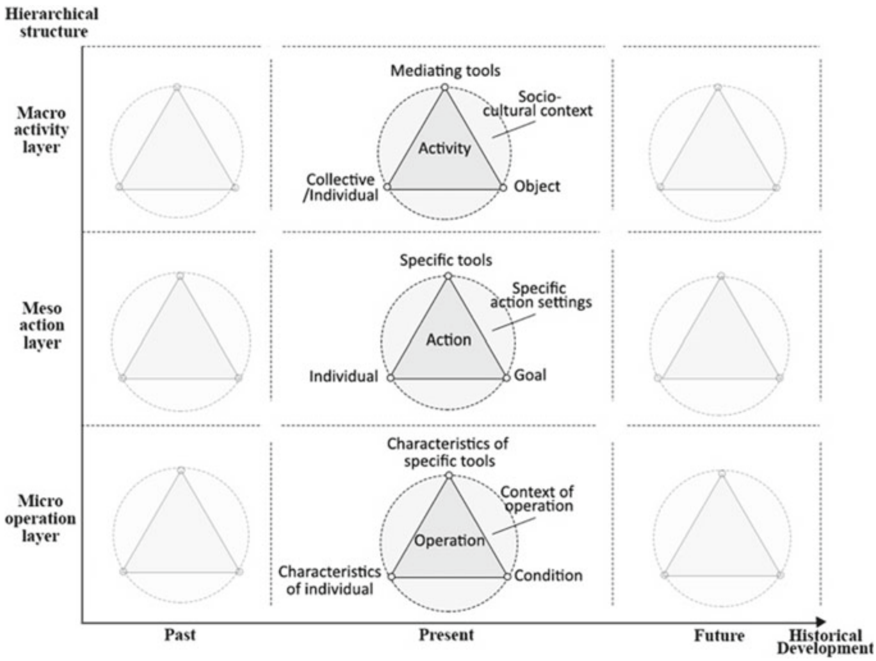

Fig. 6.1 Activity model. Adapted from Kaptelinin and Nardi (2006)

(6) Internalization and externalization. In the present paper, we focus on interpreting these theoretical concepts that the above AT models are based on.

Over the past two decades, AT has been widely applied as an analytical tool to understand the complex real-world human-artefact relation and inform implications for design [e.g. Glad (2015), Selvefors et al. (2015), Rexfelt and Rosenblad (2006), Woll and Bratteteig (2018)]. In general, insights from these studies showed that the descriptive nature of AT can enable design researchers to shift focuses from purely on analyzing individuals' needs and characteristics such as age, personality, and preferences, to the activities that the target user groups carry out, thus arriving at new knowledge to reframe problems that users encountered within the dynamic context of human activity (Norman 2006, 2013).

Furthermore, in the field of Human-computer interaction (HCI), activity theory has already been developed into a structured methodological approach for design explorations (Clemmensen et al. 2016). The concept of activity-centered design was thus proposed. Similar to the concept of user-centered design (UCD), the user (or people) is still the focus of the ACD design (Norman 2005). However, with a broader focus on the interplay between mediating tools and user activity, contextual background, and disruptions and tensions within the history and development process of user activity, ACD is regarded as an enhancement of UCD which systematically accommodates both spatial and temporal factors into design considerations (Kaptelinin and Nardi 2006; Norman 2006, 2013; Gay and Hembrooke 2004).

Despite being widely used in design research, the use of AT and ACD in sustainable design studies and the sustainable design insights that this theoretical lens can bring to product and service design have been rarely explored (Kaptelinin and Nardi 2012). The next section addresses the development process of our ACD toolkit with a literature review on the above question.

6.3 ACD Toolkit Development and Literature Insights

An overview of the toolkit development and evaluation methods is illustrated in Fig. 6.2. In the development phase, we conducted a non-exhaustive literature review on the use of activity theory in design-focused studies. As mentioned above, the specific goal of the literature review was to develop a comprehensive understanding regarding (1) How the key AT theoretical concepts were applied in design research with a particular focus on interpreting sustainability-related empirical phenomena, and (2) How these theoretical concepts were used to inform and guide practical design explorations.

We followed the literature review approach used in an existing study on the use of AT in HCI (Clemmensen et al. 2016). As we focused the overlapping area of three different aspects: activity theory, design tools, and sustainability, we narrowed down the literature search scope and categorized the search terms into three groups: Group1 (theory-focused)—'activity theory', 'activity-centered design'; Group 2 (design-focused)—'sustainable design', 'design for sustainability', 'design tool',

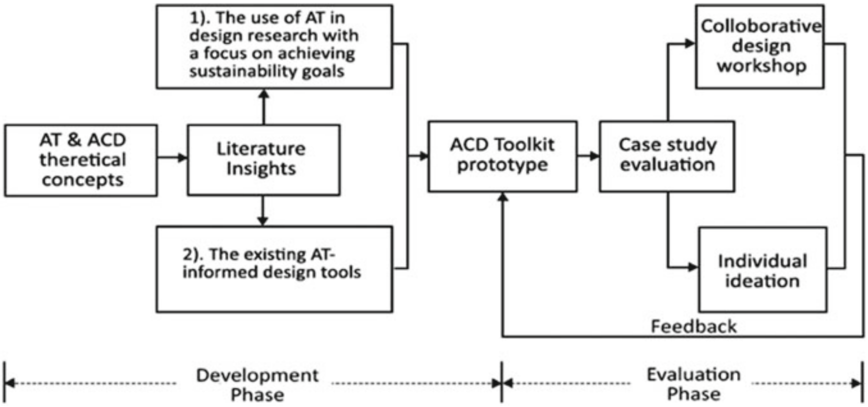

Fig. 6.2 The overview of the sustainable ACD toolkit prototype development and evaluation step

'design approach', 'design method'; Group3 (sustainability-focused)—'sustainability', 'sustainable behavior change'. Scopus was used as the search platform. Given the scope of this paper, we only summarized the preliminary review results (cut-off date for the review is 28th June 2019) which were used in the initial concept development stage of the ACD toolkit.

6.3.1 Use of AT in the Context of Design for Sustainability

AT can contribute to analyzing and framing sustainable design problems based on the following six theoretical concepts:

Mediating tools: The most fundamental concept of AT is that human activities are mediated by artefacts. The mediating artefacts can be external, such as hammers, phones, and computers, which are intended to be used as physical tools. The tools can also be internal and abstract, such as signs, models, and language (Gay and Hembrooke 2004; Kaptelinin et al. 1999). However, as design practices focus on creating products or services that have a material form (be it physical or digital), the underlying influence on user behavior is often neglected in the design process (Wever et al. 2008).

When the concept of mediating tools is used in the design of sustainable products and services, the explicit accommodation of material and immaterial perspectives of design can enable designers to consider creating impacts not only on the material production or technological aspects, but also on user behavior, norms, knowledge, and perceptions when using the artefacts, thus opening up the windows of opportunity for designers to simultaneously improve the sustainability performance of both the designed products/services and user behavior (Hoffmann et al. 2017; Novoa et al. 2018; Querol et al. 2015; Timmis 2014). We encourage designers to reflect on: How can the designed artefacts influence the way people carry out their activities? How do the designed artefacts change over time? Are these changes triggered by designers' intentions or users' practices? What effects do these changes have?

Historical development: Activity systems are not static, but under a dynamic development and transition process over time (Kuutti 2019). The way we carry out a specific activity at a specific point of time under a specific context is the result of the historical evolution of the relevant activities and tools (Kaptelinin and Nardi 2006). AT's development perspective thus is used in design to describe how the target activities and the use of artefacts change over time. Artefacts, as mentioned earlier, can shape the activities that people carry out. In turn, the artefacts themselves are also shaped and under a constant development process as the activities keep evolving (Gay and Hembrooke 2004). For example, mobile phones were originally designed as verbal communication devices that bring convenience to people's daily communication. However, nowadays the mobile phone has evolved into a digital platform that incorporates features such as cameras, notebooks, music players, credit cards and gamepads.

When applied to design artefacts that foster people's sustainable activities, the historical analysis and the development view can enable designers to assess future design opportunities and interventions in terms of facilitating sustainability from a more holistic perspective (Kuutti 2011). To be more specific, it provides designers a way to understand not only about how people perform their doings in the current situation, but also what has happened in the past, and how these past designs may potentially influence the future. This characteristic is in accordance with the feature of sustainable design—to solve the current and emerging problems and design for new forms of engagement (Kaptelinin and Nardi 2012). For example, in the investigation of the role that information system (IS) can play in tackling climate change adaptation, Hasan et al. (2017) pointed out that a historical development perspective is particularly useful to investigate sustainability problems which are often characterized by complexity and uncertainty. We encourage designers to reflect on: What were the artefacts that have been used in the target activity in the past? What are the artefacts that are currently being used? What are the changes/impacts that these artefacts will bring to people's current activity systems? And what are the corresponding possible future ways of carrying out the activity?

Sociocultural contexts: While the historical development perspective can inform a temporal lens to identify existing or potential sustainability problems within the target activities, the sociocultural context can offer a spatial and hierarchical lens which helps designers to zoom in or zoom out to investigate where sustainability problems may take place in three contextual levels: the macro sociocultural level, the specific action level, and the detail operation level (see Fig. 6.1).

For example, in a project of promoting socio-ecological sustainability in a local community in Chile, Aguayo and Eames (2017) applied AT to understand the sociocultural factors surrounding the potential use of information communication technology (ICT) as a mediating tool for community learning. It was reported that the AT-informed sociocultural understandings helped researchers to integrate the specific sustainability design solutions with the practical needs of the local community. Similar findings were also reported in another study which used ICT to promote social and environmental sustainability for elderly women in remote rural South Africa, reflections from the study showed that "AT provides a means to describe and understand the social and political dimensions of the social context" (Smith and Turpin 2017). Some key questions such as what are the sociocultural factors that may influence the sustainable usage of a specific design in people's target activities? What are these potential influences? Are there any desired social and environmental behavior that designers want to influence within the target activity systems? And how to incorporate the different needs of different members in the activity system? Can be addressed by using this concept.

Tensions and contradictions: Given the temporal (historical development) and spatial (sociocultural context) scope of human activities, AT can be also used to identify the tensions and contradictions in people's activity systems. According to Engeström (2014), tensions and contradictions within and between different components of the existing and a more advanced form of the activity are the driving forces of activities' evolution. Those contradictions include misfits, problems, tensions, incoherencies, and inconsistencies that subjects encounter when they carry out an activity (Blackler et al. 1999). When these tensions and contradictions become materialized at a given point, the activity systems may undergo a transition process in which the subject attempts to find temporary solutions to address the contradictions (van Baalen and Huysman 2003). It is under these moments that the activity system develops and adapts itself to the new context (Gay and Hembrooke 2004).

When applied to achieve sustainability goals, the analysis of tensions and contradictions helped designers to derive and accommodate design requirements to fulfill the needs of different stakeholders within and between activity systems. For example, Hoffmann et al. (2017) and Döweling et al. (2012) used AT to systematically identify tensions and contradictions between different components in IT services such as the relation between the software tools, IT project members, and management teams, which were later used to inform design goals and principles to solve the sustainability problem within an interactive system design project. Similar to that, Lin and Hsieh (2014) used the same concept to identify the problems that affected the development of a new telehealth service, the sustainability aspect of the new design was achieved through analyzing the tensions and contradictions between the telehealth service provider, physicians, patients, and devices used in the telehealth system.

In addition to the concepts of *mediating tools, historical development, sociocultural context, and tensions and contradictions*, which have been directly used in sustainability-focused design research projects, we also took ***motivations, goals and outcomes***, and ***mental simulation and actual performance*** from AT concepts into consideration. These two concepts have not yet been found to be closely connected to either identifying sustainability problems or informing sustainable design explorations. However, the concept of *motivations, goals, and outcomes* is especially useful to develop a background picture of why a particular activity takes place, what the specific motivations are, and what the corresponding actions and operations are. The transformation between mental simulation and actual performance (more commonly referred to as *internalization and externalization*) can reveal the learning and performance that is embedded in people's activities (Kaptelinin and Nardi 2006). Specifically, it enables designers to understand questions such as what users need to learn to carry out target activities, and how do artefacts undergo an internalization and externalization transition process in different contexts. Table 6.1 shows how the above six AT theoretical concepts were translated into practical sustainable design-oriented questions.

6.3.2 Requirements of AT-Informed Design Tools

The main purpose behind the existing AT and ACD -informed design tools is to guide empirical analysis and design processes (Clemmensen et al. 2016). These tools were developed into different formats such as design models (Döweling et al. 2012), checklists (Duignan et al. 2006; Irestig et al. 2004; Berlin et al. 2017), and frameworks (Desai 2007; Fjeld et al. 2002). We identified three key requirements from the review of these tools:

1. *Need for descriptive design vocabulary and examples*

Although activity theory has a descriptive nature, some of its concepts such as tensions and contradictions, mediating tools, internalization and externalization are perceived as too abstract for design practitioners to understand (Kaptelinin et al. 1999). Therefore, the jargon of academic terms should be avoided. Concrete descriptions and design-related vocabulary are needed so that design practitioners with no prior knowledge of AT can directly use the theoretical concepts in their sustainable design practices. In addition to that, according to (Bødker and Klokmose 2011), in terms of AT, design examples are proved to be helpful to bridge the gap between theoretical concepts and design practices.

2. *Need for flexibility*

Design practitioners' work scenarios differ from each other. In some cases, designers may work individually while in other cases collaboratively with other design team members or co-design with potential users. To support design activities in these real practices, design tools, especially ideation tools, need to be able to adapt to different scenarios and take users with or without professional design background into account.

3. *Increase interactivity*

To facilitate designers' adoption of tools in their ideation process, one way is to increase interactivity, so that users of the tool can be more engaged in the design process. For example, an AT interview question checklist was proposed by (Duignan et al. 2006) to help interviewers to interact with interviewees on the same theoretical basis. Similar to that, a program called ActivityDesigner (Li and Landay 2008) was

Table 6.1 Translating sustainable design implications from AT theoretical concepts to design-oriented questions

AT concepts	Implications to sustainability aspects	Examples of design-oriented questions
Mediating tools	Facilitate desired sustainable changes or retentions both on material and immaterial mediation of the target activity systems	What would happen if your design is flexible enough to adapt to different scenarios of the target activity? Can you design features which support multiple actions that users usually perform within the target activity?
Historical development	Learn from the evolution of target activities, discover the knowledge embedded in the development of artefacts, and explore sustainable design opportunities with a temporal lens	Can you design some features so that users immediately understand how to use the designed artefact based on their past experience? What are the potential changes that you aim to achieve/avoid in users' target activity systems? Can your design induce/prevent such changes based on the activity's developmental history?
Sociocultural contexts	A spatial lens which helps to zoom in or zoom out to identify the socio-cultural needs and factors that may influence the sustainability aspect of the designed artefacts	Are there any social and environmental concerns that you want to influence the users' activity through your design? Are there any cultural differences within the user activity? Can you learn from how people carry out the target activity in another culture?
Tensions and contradictions	Derive and accommodate sustainability design requirements by identifying tensions while fulfilling the needs of different stakeholders within and between the target activity systems	Are there any user goals that are hard for users to attain because they couldn't adjust the design? What if your design aims to solve that specific problem? Are there any user goals that are not supported by the tools at hand, so that users have to find some other supportive tools to carry out the target activity?
Motivations, goals and outcomes	Understand why the subject carries out a specific activity in a specific context to achieve a specific goal	Are there any unexpected user goals or needs that may become attainable through your design? Can you design to enable users to attain a series of different goals in a row?

(continued)

Table 6.1 (continued)

AT concepts	Implications to sustainability aspects	Examples of design-oriented questions
Mental simulation and actual performance	Identify what users need to learn to carry out the target activity, and how do artefacts help users to undergo the transition process between mental simulation and actual performance	Can you design some features so that the user is willing to learn how to use your design even if it requires effort and time?

developed to support designers to breakdown users' activities and reconstruct the activities in a digital platform. Apart from the engagement, the interactive format of the tool can also make the heavy theoretical concepts be more easily applied to address real design issues (Bødker and Klokmose 2011).

6.4 Introduction to the ACD Toolkit Prototype

To develop the first version of the sustainable ACD toolkit prototype, we incorporated the literature insights on the use of activity theoretical concepts in solving sustainability design issues (see Sect. 3.1) with the toolkit development requirements we have identified above. We decided to use a physical cube as a way to represent the key theoretical concepts of AT to designers. As illustrated in Fig. 6.3, the Activity Cube is bounded by six facets which represent the six key concepts of AT summarized in the preceding section: (1) Mediating tools; (2) Historical development; (3) Sociocultural contexts; (4) Tensions and contradictions; (5) Motivations, goals, and outcomes; (6) Mental simulation and actual performance. In order to avoid jargon and misinterpretation of the above theoretical concepts, each concept is translated by the authors of this paper (see Table 6.1). Furthermore, by transforming these key theoretical concepts from the conventional two-dimensional triangle AT model (see

Fig. 6.3 Up: ACD card; Bottom-left: Activity Cube; Bottom-right: The deck of ACD Cards

Fig. 6.1) into a three-dimensional physical cube, we intend to use the form of dice play to introduce elements of randomness (Bengtsson et al. 2018) and thus provide a more interactive way for design practitioners to unfold the different aspects of human activities.

To better support the use of the Activity Cube in designers' early-stage design ideation process, we also developed the Activity Design Cards to provide questions and examples for designers to explore. The Activity Design Cards are comprised of six categories which match with the six facets of the Activity Cube. Each card is comprised of two parts: an activity-centered design question and a corresponding design example (see Fig. 6.3). The design examples we illustrated in the cards are extracted from the products and services that people are familiar with in their daily life contexts. The purpose is to help design practitioners to reflect on the questions through the support from design examples without the need to spend further efforts in learning the background of the theory. Currently, there are 24 activity design cards, covering all six facets of the Activity Cube. Note that the deck of cards will be expanded in the next prototype iteration. The current version is available from the authors upon request.

6.5 Case Study Deployment: Reducing Household Food Waste Through Packaging Design

6.5.1 Case Study Background

At this early concept development stage of our sustainable ACD toolkit, we aimed to gain insight in terms of how the ACD toolkit can be used in designers' ideation process and collect feedback regarding the usability of the toolkit. We tested the toolkit in an ongoing case study "Design On-pack Information Attributes to Influence Consumer Household Food Waste Behavior" (Chu et al. 2019). In the project, the tool was tested in both collaborative design workshops and individual ideation sessions. We invited both design researchers and food industry practitioners to participate in the study. This combination of participant background and research settings allowed us to understand how the toolkit can be used by not only professional designers, but also people without any solid design background, not only in group scenarios but also in individual settings. The design brief that all the participants received was "In order to optimize people's correct usage of date labels and storage guidance, what packaging or non-packaging product/service design concepts can be developed?". Observation notes, audio recordings and participants' sketches were collected in the workshops and interviews. All of the workshops and interviews were transcribed.

6.5.2 Applying the Toolkit in Collaborative Design Workshops

Two design workshops were conducted to explore how the ACD toolkit can be used in collaborative group idea generation sessions. In total, 12 participants were recruited through the authors' professional networks. 8 participants were Ph.D. candidates who worked in the computer-aided and engineering-related design field. The other 4 participants specialized in product and service design. Given their knowledge and experience in design ideation, these 4 participants (D1–D4) were regarded as design experts in the present study. We evenly distributed the 12 participants into two workshops based on the participants' background. Each workshop consisted of 6 participants, 4 participants with basic design knowledge background, 1 junior design expert, and 1 senior design expert.

The design workshop was comprised of three steps. In the first step, all participants were given a brief introduction of the on-pack date labelling design challenges. Following that, we carried out a 20–30 min focus group discussion for participants to reflect on the food consumption topic and exchange opinions. In the third step, a brief introduction of how to use the ACD toolkit was given to all participants. After that, participants were split into two groups. Each group was given one ACD toolkit and asked to use the toolkit to generate early-stage design ideas. Each idea generation session took around 5–10 min. After each session, the two groups were asked to briefly present their interpretation of the Activity Design Cards with their design ideas that were derived from the cards. The third step took around 30–40 min. In total, the design workshop lasted for approximately 75–90 min.

During the workshop, the researcher mainly played a moderator's role. After the workshops, follow-up one-to-one interviews were conducted with the 4 design experts we identified previously. The goal of the interview was to gather design experts' opinions regarding the content and the usability of the toolkit from an expert's point of view, thus helping us to develop an in-depth understanding of the strengths and limitations that the ACD toolkit may have in real design practices.

6.5.3 Applying the Toolkit in Individual Ideation Session

In order to evaluate the use of the toolkit in individual usage scenarios, we recruited 4 participants (P1–P4) who have worked in the food packaging industry. The design challenges that the participant received were identical to the collaborative workshops. Each interview lasted around 45–65 min. Similar to the design workshop procedures, first, we started the interview by introducing the specific design challenge. And then we encouraged participants to reflect on their usage of date labelling attributes in their daily food consumption activities. Following that, we carried out the individual idea generation session by introducing the ACD toolkit.

6.5.4 *Feedback Regarding the Concept of the Toolkit*

6.5.4.1 Does the Toolkit Help to Frame and Generate Design Ideas to Solve Sustainability Issues?

Overall, participants developed ideas ranging from simple solutions such as (1) Providing a visual representation of how a spoiled food product can look like on packaging, and (2) Mobile applications for better organizing food shopping list, to technology-focused concepts such as (1) Smart on-pack date label which can give real-time feedback of the quality of food items, (2) An intelligent fridge which can remind users of food status, and (3) A QR code that provides product traceability to consumers.

All the above ideas were informed by the collaborative use of the ACD toolkit in design workshops or independent use in individual ideation sessions. For example, by using the card—"*Can you design features which support multiple actions that users usually perform within the target activity [Food consumption]?*" (in the category of mediating tools), P3 came up with the idea of providing recipes for consumers to better use food items that are close to its expiration date, thus preventing unnecessary household food waste. Similar to that, workshop participants also developed ideas of informing consumers how to deal with food items that just past the 'best-before date' from the design example presented in the card—"*Can you design to enable users to attain a series of different goals in a row?*" (In the category of motivations, goals, and outcomes). Furthermore, inspired by the card—"*Can you predict the potential technology advancement that would take place and can you incorporate the technology in your design?*" (in the category of sociocultural contexts), P1 developed the idea of using a QR code as an interface on food packaging for consumers to trace the information of food such as when and where it was produced and transported, thus leading to more informed food purchase and disposal decisions.

Through comparing the toolkit with other existing design ideation tools, one of the design experts indicated that the ACD toolkit can help to put particular focus on how to incorporate different sustainability aspects in design by saying: "*the other ideation cards are very general, but this tool is specific. This would put you in a very specific mind, there would be tips and directions that lead you towards sustainability*" *(D1).*

6.5.4.2 Which Elements of the Toolkit Are Supportive and Which Elements Cause Confusions?

In terms of the usability of the toolkit, both the design experts and food packaging industry participants without any design experience reported that they enjoyed the interactivity of the toolkit, especially the mechanism of playing with a physical cube as dice and picking up the corresponding cards according to the result of the dice. For example, "*The dice is rather interesting and fun compared to other ideation cards,* *which are just cards.*" (D1), "*It is funny* [to play] *with the dice, with the concept of randomness, rather than just picking a card.*" (D2)

However, regarding the presentation of the Activity Design Cards, the text description on the card was perceived by the design experts as redundant. Both design experts and participants with non-design backgrounds went directly to look at the images of activity-centered design examples illustrated on the cards. Suggestions were made by design experts that the question part should be clear and easy to read, the relevant ACD examples can be separated from the design questions and moved to the back of the cards.

Regarding the potential usage of the toolkit, all design experts indicated that if they would use the tool in their real design process, they would use it mainly in the early design ideation and concept development stage where they just started exploring a specific problem with the need to generate as many ideas as possible. For example, D3 indicated that the toolkit can be helpful to "*induce new direction in the stage when you feel depleted, focused on some areas where you have neglected previously.*"

6.6 Conclusion and Future Work

This paper makes two contributions to the topic of design for sustainable behavior and circular consumption. First, it reviews relevant AT-based design and sustainability literature, and explores how to use an activity theoretical lens in product and service design to facilitate people's sustainable activities. Second, based on the theoretical exploration, it presents the development and evaluation of an activity-centered design toolkit prototype, which aims to help design practitioners to better frame and develop ideas in their early design ideation stage to solve sustainability problems in users' dynamic activity systems.

Overall, the result of the evaluation indicated that participants used the toolkit as an interactive approach to take different aspects of user activity into design considerations. It worked as an entry point which allowed participants to engage with complex sustainability issues within users' activity systems. However, since the ACD toolkit is in its early concept development stage, the prototype is not yet ready to be applied in actual sustainable design practices. Rather, it is an illustration of how AT concepts can be translated for and used by design practitioners with no prior knowledge of AT. According to the feedback collected from the participants, several usability problems need to be addressed. The most common suggestion is to reduce the redundant text descriptions and adjust the layout of the Activity Design Cards.

For the next iteration, we plan to first solve the identified usability problems, and then further evaluate the design vocabulary and questions extracted from AT with researchers and design practitioners. Following that, the revised sustainable ACD toolkit prototype will be tested in other design case study settings.

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Chapter 7
Strengthening Aesthetic Individualization in Product Design to Enhance Customer Loyalty and Sustainability

Lisa Hagedorn, Gerald Kremer, and Rainer Stark

Abstract This paper analyzes how the aesthetic individualization of products affects product sustainability. Furthermore, it depicts the need to strengthen the degree of individualization in mass customization concepts and reveals ways to enable stronger participation by customers in design processes. Customers often replace products before the functional end of the product's life cycle. This psychological obsolescence of products is caused by multiple factors. Frequently addressed reasons are the unsatisfied need of customers for uniqueness in product design and the absence of sufficient attachment to the product caused by insufficient functional/aesthetic identification of the customer with the product. One way to tackle these deficiencies is by addressing and implementing the concept of mass customization. A demographic survey presented in this paper indicates that the majority of customers want more creative freedom in designing their products and a stronger participation in the design process. It also shows that stronger individualization leads to a higher degree of product attachment. A qualitative follow up study held a workshop for user-centered design with relevant stakeholders: designers, manufacturing engineers and customers of different age groups. In this workshop the needs of potential users were analyzed, and possible solutions were created and subsequently evaluated.

Keywords Sustainable product design · Customer loyalty · Individualization · Aesthetic principles in product design · User-centered design

7.1 Introduction

The greatest challenges that the industrial sector is facing nowadays are the reduction of resources that are being used in production processes and the reduction of consumer consumption. At the same time, the quality of life and the customer satisfaction should at least be maintained, if not increased. When considering the growing

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population of developing countries, it is ethical to assume that these nations aspire to the same living standards that the developed countries are enjoying.

Sustainable development strategies that address these needs cannot be implemented without technological progress and new consumption strategies. However, in the past few years, it has been observed that consumer behaviour is less sustainable in many sectors. It is interesting to mention that more and more products are being sold as 'ecologically sustainable 'certified products (Steinemann et al. 2017). Even so, overall social consumption has become less sustainable during recent years. To be more specific, products are used for less time than they could actually be used. Products are thrown away before they get broken. This phenomenon is called psychological obsolescence or obsolescence of desirability (Packard and McKibben 2011). Companies are often accused of designing products in such a way that they become unusable prematurely in terms of function or material. There are intriguing examples of companies that have actually been practicing this strategy of stimulating unsustainable consumer behaviours for economic gains. Apple and Samsung have already been convicted for this behaviour (Autorità Garante della Concorrenza e del Mercato 2018).

Even so, companies are not the only responsible party. In fact, the level of usage of products by consumers continues to decline, indicating a tendentially decreasing level of civic responsibility in our society. The phenomenon of psychological obsolescence is becoming a worrying reality that the industrial thinkers need to address as fast as possible.

Product designers, who are responsible for the aesthetic perception of the products, can and should make an important contribution in this matter as well.

One of the reasons consumers exchange products too early is the aesthetic of the product. Consumers express themselves through the look and feel of their belongings, to satisfy the need for uniqueness through products. As mass production leads to market saturation for a given product, this need cannot be sufficiently satisfied. In addition, mass produced goods cannot perfectly satisfy the individual aesthetic wishes of all consumers.

The aesthetic individualisation of products can counteract this and allow customers to have stronger product attachment and thus use the products longer.

Consumers tend to be more willing to repair products instead of replacing them when they have a relative high level of product attachment (Govers and Ruth 2004). The degree of consumer-product attachment is defined as "the strength of the emotional bond a consumer experiences with a durable product" (Schifferstein and Zwartkruis-Pelgrim 2008). At the same time, the concept of product attachment is of great importance for companies. Customers who have a high product attachment also have an increased connection to the manufacturing enterprise. Companies benefit from increased customer loyalty since it generates tendentially increased repurchase rates, increased rate of product recommendation, and an increasing brand value for the company (Pedeliento et al. 2016). In this context, the generation of high levels of product loyalty would consequently be more ecologically sustainable since resources would be more efficiently used. Higher levels of product loyalty also contribute to sustainable corporate growth.

One of the currently most popular ways to individualize the aesthetic of a product is mass customization, which will be described more detailed in the upcoming chapter. Still, the current methods of mass customization limit the possibilities of customers to integrate their ideas into the design process since modules which are being put together by the customers are predesigned by product designers before the customer is integrated into the design process. Therefore, the freedom of the consumers to influence the aesthetic properties of the product is always limited and the fit of the aesthetic features of the product and the needs of the consumers is not necessarily given.

This paper will give insights on how aesthetic mass customization influences the attachment a consumer has to a product and thus the sustainability of a product can be improved. More than that it examines the limits of mass customization to always find the aesthetic fit to the customer's needs. Based on these findings a research questions is analyzed. It is to be found out, if a greater degree of product individualization correlates with a greater degree of product attachment, product longevity and thus sustainability. Furthermore, it is examined for which product categories a higher degree of individualization is wanted. In a next step an open-result workshop with relevant stakeholders was conducted to collect possible strategies to strengthen degree of aesthetic individualization while at the same time to take into account the principles of the efficiency of mass production.

7.2 State of the Art

There are a large number of descriptive models of product-consumer attachment. The drivers for increased attachment are diverse. As mentioned by several authors, the main factors that generate an increased product attachment are the product's aesthetic and functional fit to the consumers' specific needs and wants, the personal memories that one associates with the product, and the temporal expenditure that consumers have to make in order to acquire the products (Schifferstein and Zwartkruis-Pelgrim 2008; Mugge et al. 2009). Many of the drivers for increased product loyalty can be observed in highly individualized products. Mass customization is a frequently used approach for individualizing products. In the following section of the paper, current principles of mass customization are briefly presented. Afterwards, we investigate how the integration of customers into the design process can be further strengthened so that customers have a stronger connection to the products and become more ecologically and economically sustainable for the manufacturing company.

7.2.1 Mass Customization

The principle of mass customization was decisively influenced by Joseph Pine. He was one of the first scientists to popularize the term as early as 1992. Pine defined

Mass Customization as “developing, producing, marketing and delivering affordable goods and services with enough variety and customization that nearly everyone finds exactly what they want.” (Pine 1993). In the following years, the principle was increasingly addressed in the scientific world from a corporate perspective. Tseng and Jiao define Mass Customization as “producing goods and services to meet individual customer’s needs with near mass efficiency” (Tseng and Du 1998). Customer-specific mass production can be differentiated in various ways. Several categories of customer-specific mass production are conceptualised based on the type of individualization (Reichwald and Piller 2009). Among these categories one can identify the following: individual specifications of the consumer, specific customer functionalities, and specific aesthetic product characteristics indicated by the consumer.

The individualization of products can be divided into different types. Products can be individualized aesthetically, functionally, and according to desired dimensions. In this paper the aesthetic individualization is examined in particular.

Reichwald and Piller formulated a detailed description of Mass Customization. The authors identify four principles that construct the basis of mass customization: customer integration in the design of products, an increase in perceived benefit from the products, financial advantages and the fixed solution space for allocated designs (Reichwald and Piller 2009) (Fig. 7.1).

The subjective benefit of the products to each customer is higher compared to conventional products because they are more adapted to the needs of the customers. This way, companies achieve a differentiation advantage against traditional producers.

Reichwald and Piller define the concept of space allocated for generating solutions as the multitude of standardized processes that are constant and stable and that are necessary to achieve individualization of products. In mass customization, the products are individualized, but the structure of all processes is standardized. This approach is intended to ensure a high quality of production and low costs. In addition to production, the design process also needs to be standardized. The principle of customer integration mentioned by Reichwald and Piller is defined as a co-production or a co-design process. Important to mention in this context is that customers cannot design elementary product features themselves, but have the opportunity to choose from variations of components, i.e. modules, pre-developed by

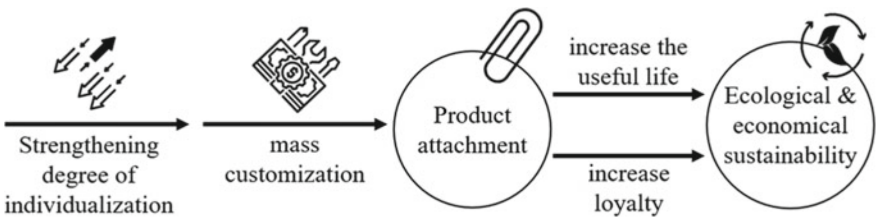

Fig. 7.1 Schematic visualization of the papers content

designers and consequently they manage to configure their desired product. To make the selection, customers use a so-called interaction or co-design system. The most common practice is described by Piller.

According to this, consumers can select a basic product at the beginning, which they can then adapt virtually through several further modules. At the same time, a plausibility check of the selected modules runs in the background of the system each time another module is selected. If all selected parts are confirmed by the system and the consumer is satisfied with the final product, the product can be manufactured (Reichwald and Piller 2009).

The configuration process can take place either offline, e.g. in the manufacturer's shop, or online. In the offline environment, the configuration can be operated either with the help of a representative of the manufacturer or by the customers themselves. In the online environment, the process can either run according to a fixed procedural sequence, an unsteady sequence or completely freely (Reichwald and Piller 2009) (Fig. 7.2).

The space allocated for generating solutions has a decisive role on the success of the production process. In the co-production or co-design process, the product structure should already be optimized for the mass customization process. For example, standardized and configurable modules should be used (Lindemann and Reichwald 2006). The product structure is often divided into a fixed and a variable area. The variable area can be mandatory or optional. In addition, a distinction is made between the situation in which the variable area was previously divided into selectable options and the situation in which the variable area is defined as a free space. Consequently, the space allocated for generating solutions always represents a finitely limited number of product variants (Lindemann and Reichwald 2006).

Customers have new roles to play in co-production or co-design processes. The designer is no longer solely responsible for the aesthetic features of the product. The customer himself is involved in the product development. The designer also has the new role of transferring knowledge (and responsibility) to the customer. This means that both the designer and the customer should develop new skills needed for the new production strategy to be successful. In the mass customization process, the customer is no longer only informed about the product selection, but it is also implicated quite early in the creative process (Sanders and Stappers 2008).

7.2.2 Potentials and Challenges

Mass customization can therefore be a possible coping strategy that could stimulate consumers to use products in a more sustainable manner. At the same time, it opens the possibility for companies to gain advantages in the form of valuable information regarding their consumer wants and needs but also in the form of increased customer loyalty. At the same time decisive disadvantages can be identified. The space allocated for solutions (that mass customization has) is always limited. In the last step, customers can sometimes refine the surface of products with samples, photo prints

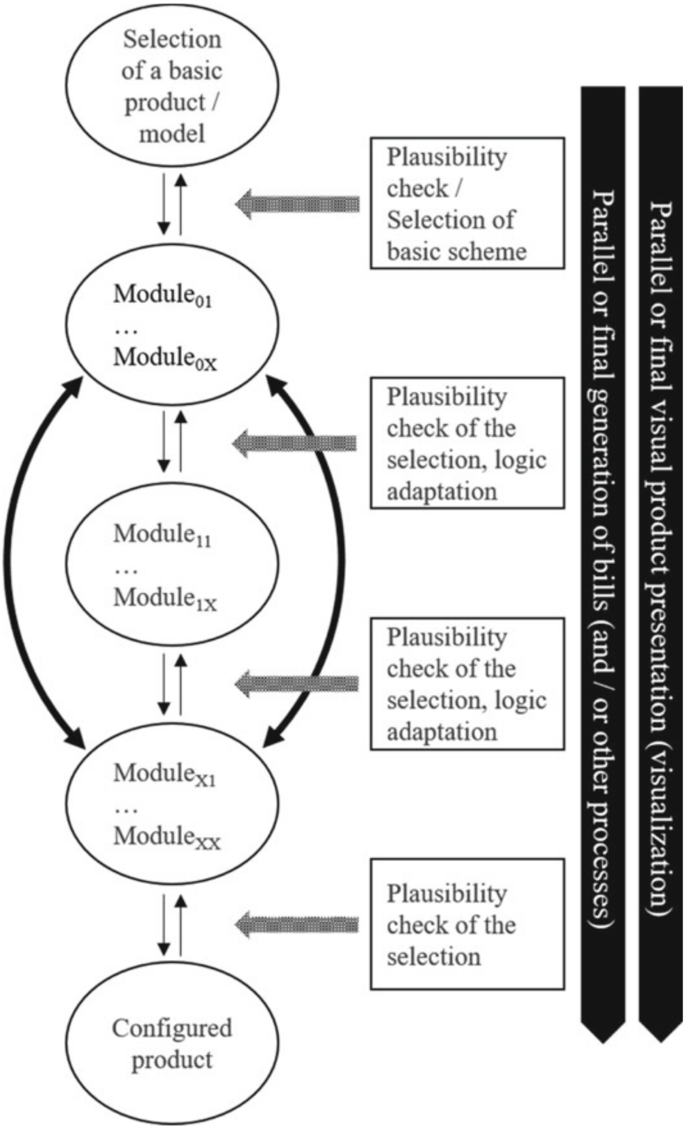

Fig. 7.2 Schematic representation of the co-design process. Own chart in refence to Rogoll and Piller (2003)

or their own drawings. However, it is not yet possible for customers to change the structure of entire modules. Customers are therefore always limited in their mass customization processes. Before the co-production or co-design process, designers create modules that can be selected by customers. From the customer's perspective, mass customization is basically a mass production process that offers a wide variety of variations. For the customer the space allocated for generating solutions is always limited and dependent on the designer‘s concept for the product. However, the aesthetic needs and wants of the customer cannot always be predicted.

A complete functional and aesthetic fit cannot therefore be guaranteed for all customers. Nonetheless, a tendentially stronger functional and aesthetic fit of the product is essential for achieving increased levels of product-consumer attachment, and this in turn can lead to greater product sustainability. Also the need of uniqueness, which is important when it comes to the product attachment of the customers, cannot be properly satisfied by mass customization, because individuals are able to use the same components for their designs.

7.3 Research Approach

Mass customization currently offers the greatest possible individualization option on the market. However, the customer's customization options are limited to modules designed by designers. The degree of individualization is limited.

It is unclear if a greater degree of individualization than the customization levels that can be found in today's industry is even desired or recommended by customers. This assumption still needs to be proven.

It has also not yet been proven whether a stronger degree of individualization actually leads to an increase in product attachment and longer usage periods of the products. Furthermore, no studies have been conducted to clarify which products consumers want to individualize to a greater degree. It is also unknown how a stronger degree of individualization can be achieved compared to today's methods of mass customization. Since such a concept has not yet been explored, no requirements have been defined on the system or the users of the system.

A mixed-method approach was chosen to investigate the topic more closely. An empirical study was conducted to determine whether customers would like to expand the space allocated for generating solutions and whether this would have the positive effects mentioned above. In addition, the study investigates for which product categories consumers have the greatest interest in achieving increased levels of individualization. For the second part, a qualitative research approach was chosen.

It was additionally investigated how a stronger aesthetic individualization can be possible taking into account cost and time efficiency and the user experience. To find this out, a qualitative research approach was chosen.

A workshop with relevant stakeholders was conducted for this purpose. The workshop configuration was based on the pre-given structure respecting the standards of the German Institute for Standardization which is formulated for the design of interactive, human-cantered systems.

7.3.1 Study Aim and Results

An online survey with 120 participants was carried out. More women than men took part in the survey. 63% were women and 36% were men. The oldest participant in the study was 72 years old while the youngest was 18 years old. The average age of the respondents was 32 years. The medium age was 29 years.

The survey contains a total of six parts (Introduction of the survey, Opinion on customer-specific mass production, Opinion on an extension of individualization, Information for the workshop, Information on demography, Conclusion of the survey). However, only a small excerpt will be given here to show the most important facts.

In response to the question of whether the participants already had experience with customer-specific mass production, 21% answered yes. 72% had no experience, but were interested. Only about seven percent had not yet bought such a product and could not imagine acting differently in the future.

The respondents were also asked: "Would you have a higher bond to the product if you could design it more strongly than with "normal" individualization?" Here 73% replied that they would have a higher bond to the product if they could co-design it with a designer. 13% would have a higher bond with conventional custom mass production. 14% said they had the same product binding in both cases.

Participants were then asked to choose which product they would use longer. 9% said they would use a normal individualized product longer, 42% said they would use the product longer if it was more individualized. 49% say they would use it the same length of time in both cases.

In addition, the participants were asked which products they could imagine to be extended customer-specific mass production. Multiple selection was possible. Most customers were interested in *furniture* (34% of the votes cast) and *clothing* (30% of the votes cast). 13% of the votes were for *means of transport*, 10% for *household articles* and a further 8% for *electronic articles.*

Among the items mentioned were means of transport, household utensils and electronic goods.

It can therefore be deduced from the survey that an individual design of the products leads to a higher product binding and thus more sustainability. Furthermore, it can be stated that an extended customer-specific mass production is desired by the customer.

7.3.2 Co-creation Workshop

The results of the first part of the investigation revealed that a stronger individualization of the aesthetic features of the product has a positive influence on the product attachment of the customer (as stated above). The second part of the investigation had the goal to find out how to implement a stronger product individualization in the industry, while maintaining at the same time the advantages of mass customization. For this purpose, a workshop was held with relevant stakeholders for the process. The structure of the workshop was based on a model developed by the German Institute for Standardization. The DIN EN ISO 9241-210 law provides a guideline based on which interactive systems can be designed with human-centred design principles (Deutsches Institut für Normung 2011). The design process is divided into four activities. First, the context for usage is described, then usage requirements are specified. After that design solutions are developed, these solutions are tested and finally evaluated. The form of the workshop was chosen because creative solutions for a possible individualisation process were to be found within a short period of time. The most important people who will ultimately use the process should jointly develop solutions and evaluate them. The fact that the users of the system come from different fields of expertise was also intended to achieve a symbiotic creative solution finding. In addition, the form of the workshop was chosen because it is designed to draw a holistic picture of the individualisation process. It is designed to define clear requirements for and from the users. In addition, the entire technological and social environment of the users is to be taken into account.

7.3.2.1 Workshop Participants

A heterogeneous group of nine participants of central importance to the process was selected to conduct the workshop. In the previous study it was revealed that consumers have, among other things, a high interest in a stronger individualisation of clothing. Producing clothing is quite different from other categories of products when it comes to the design process, marketing, manufacturing and training designers and manufacture experts. The participants were organised in two groups: one group had the goal to formulate strategies for developing a process to strengthen the degree of individualization for clothing and the other group had the goal to develop a stronger product individualization for other categories of products. At the same time this group was briefed with the findings of the survey stating that costumers are interested in more individualization for products in the field of furniture, means of transport, household and electronic articles. The groups consisted of consumers belonging to different age groups. In addition, the second group included a production engineer and a product designer. In addition to the consumers, the first group also had a fashion designer and a textile production engineer. The whole workshop was coordinated by a professional moderator.

7.3.2.2 Structure of the Workshop

The workshop lasted three hours and was divided into three parts. In the first step all participants introduced themselves and the moderator introduced the participants to the topic. He explained the content and structure of the workshop, the research question and the main features of Mass Customization. In addition, the participants were taught that people can be divided into different creativity classes. As a stimulator, the participants were briefly trained in methods of Design Thinking and various possibilities were addressed on how processes can be presented in an understandable manner. The first part also presented the findings from the previous study.

Afterwards, the central part of the workshop began. The first activity, understanding and describing the context of use, was initially carried out by the whole group with the help of the moderator. The goal of the process was described as follows: ‘to create a co-production or co-design process that, with the help of consumers, has a targeted and simple influence on the aesthetic characteristics of the product and thus obtain a product that they enjoy using for a long time’. In order to assure that all the participants have the same knowledge basis relevant for the workshop, a brainstorming session was before the workshop with the goal to name and explain possible technologies in product design, visualization and manufacturing areas. Subsequently, the requirements for the system were further specified in the subgroups fashion (first group) and product (second group). Consequently the design solutions were conceptualized in the groups. After brainstorming, both groups presented their results to each other, evaluated them and optimized them.

7.3.2.3 Execution of the Workshop

The presentation and introduction to the topic went according to plan. For a better understanding, an elementary basic blueprint of a process diagram was designed for the co-production, co-design process. The process diagram then served as a starting point for the description of the usage context. The customers were divided into different creativity classes in order to offer them an effective and satisfying process experience. The participants decided that the needs of the customers in the two groups (fashion group and product group) already differed so strongly that a subdivision into the subgroups was necessary. The groups worked on the topic in separate rooms.

7.3.2.4 Product Designer Group

The group decided that customers should be divided into creativity classes before the actual process begins and then go through the process differently. The customer’s need was described as the ability to purchase a unique and customized product. The group decided to not make a detailed profiling of the customers that would include the different creativity classes. The stakeholder analysis in this group had therefore already been completed. Almost all activities of the co-production, co-design process were observed by participants of the workshop together with the customers. The participants concluded that the technologies used for the co-design process as the most important drivers for the success of the process. In the opinion of the participants, virtual or augmented reality should be used when designing production since these tools have the ability to support customers to imagine a product before it was produced. In the furniture sector in particular, ordinary monitor displays are not sufficient to imagine how a product looks and works. Customers have problems for example to imagine the actual sizes of the final product. However, a simple display of the product on a monitor should be possible at the customer's wish. It is also important during the design process that an algorithm checks continuously when the product is ready for production. The process should run in the background and warn the customer at an early stage if he reaches restrictions with regard to manufacturability. In addition, a psychological profile of the customers should be drawn up before the beginning of the survey so that they can then be divided into groups with different creative abilities and different levels of knowledge of design processes. Customers should then be able to design completely independently with a program, using remote advice from a human designer or a chat- or co-design-bot. At the same time, consumers should also be able to buy products designed by other consumers. This way, customers could satisfy their need for a 'unique' design without needing to create In addition, customers should be able to further modify existing designs from other customers or from designers who have developed the basic bodies, so that they can quickly and easily develop a unique and specific design. In addition to determining a geometric shape, customers should also be able to select preferred materials from a material library. The process should be able to function both online and offline. It was not yet defined which technology should be used by the customers to create their designs. The group documented the results in the form of an affinity diagram.

7.3.2.5 Fashion Design Group

The fashion design group started by listing the relevant stakeholders in its processes. These were the consumers, designers, editors and tailors. Characteristic for the consumers is that they have different ideas about their clothing should look and be and also different measurements, sizes. At the same time, they are creative in different manners, so this is why they are looking for different products and need products for various occasions. In the same time, consumers are often unable to correctly evaluate themselves and indicate precisely their body measures. Even designers often evaluate differently the sizes that they produce. However, their experience and profession helps them in making more precise evaluations of sizes and measurements. In the design process, designers often have ideas about how to implement the production. In addition, designers have the technical skills (regarding form, materials, colours, etc.) necessary to create a successful piece of clothing. The activities of the cutters are difficult to document since they vary greatly from garment to garment and it is difficult to standardize. Only very simple sewing tasks can currently be automated.

After this phase, the group started to create a flowchart and added notes to it. Figure 7.3 illustrates their results.

Throughout the workshop, many important findings regarding production feasibility and other systems requirements could be developed. An extension of the

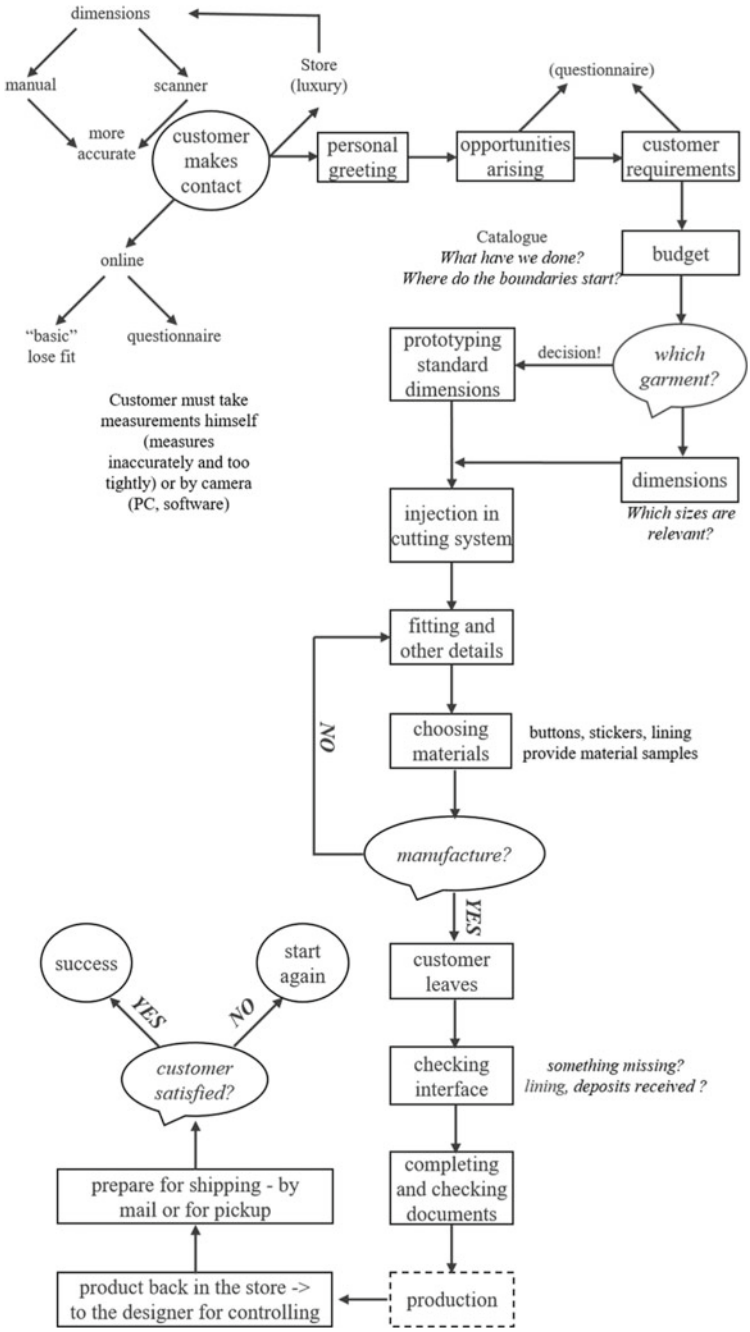

Fig. 7.3 Results of the fashion design group

customer-specific mass production is possible. However, it is not possible to derive a standardized ideal procedure for a process that allows a greater degree of individualization for every conceivable product.

7.4 Discussion and Conclusion

Overall it could be proven that an extension of individualization is possible and more sustainable than mass produced goods. It could be found out that customers not only use stronger individualized goods longer but also build up a higher product attachment and thus build a stronger loyalty towards the brand. This means that the product can be more sustainable, by encouraging the costumer to use the product for a longer period of time, which means a costumer rebuys the product less often.

A greater degree of individualization must be formulated for each product, since consumer needs as well as design and manufacturing processes for individual products differ greatly from one another. A basic guideline for the implementation of individualization strategies, as proposed by Kaneko et al., is possible and its structure is also reflected in the process diagrams of both workshop groups. Kaneko et al. describes the procedure for designing an individualization process of a product in the process steps readout, goal setting, solution development, production and realization (Kaneko et al. 2018).

In the case of an especially strong degree of individualization a more user centered description model was chosen. It was possible to identify drivers that are important for the success of such a process. The most important drivers that were identified in the investigation of the paper and possible implementation strategies that derive from their characteristics are the following (Fig. 7.4):

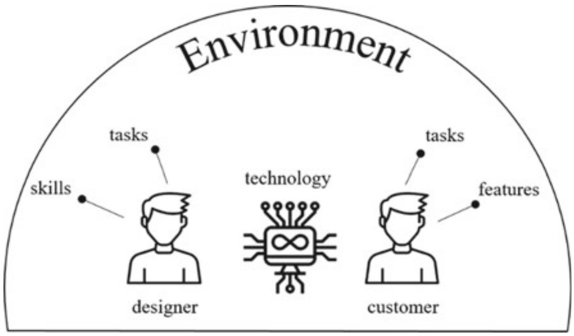

Fig. 7.4 Schematic visualization of the product eco system

7.4.1 Stakeholders

The most important stakeholders in the design process were the consumers and the designers. The two categories of stakeholders have very different characteristics and roles. Above all, the designers should have the ability to stimulate the consumers to implement their own ideas. It would therefore be conceivable that designers would have to undergo a stronger pedagogical training to be able to support the customers in the design process. Elisabeth Sanders has drown a similar conclusion for the future of designers (Sanders and Stappers 2008; Sanders 2006). In addition to the work mentioned in the processes described above, the activity of designers was above all in the area of consulting and quality control of the designs that were created. Furthermore, it would be conceivable to assume that their designs could serve as inspiration for future consumer creations. Moreover, the specific need of a software solution for the design process were conceptually identified in both groups. A further task, responsibility of the designer would thus be the conception of such a software solution.

The most important stakeholders in the system were the consumers. Since it is an essential characteristic for the design process, their creative ability was discussed in the workshop. The distinction between the four creative groups described above seems to make sense in this context. The description of the classes was based on the classification by Sanders. According to Sanders, people can be divided into Doer, Maker, Adapter and Creater. Each class is correlated with different forms of creative abilities and different levels of motivation (Sanders 2006). It was found out that all the needs and wants of the consumers can be addressed through a needs-based production process. The role of the consumers includes the design of the product, but mostly the decision making process which is accompanied by the designer. The role of the customer can be defined as the selection and the purchase of an already individualized product, in the adaptation of an already individualized product or in the accompanied or even completely independent creation of the product.

7.4.2 Environment/Technology

An implementation of the extended individualization is thinkable both in a shop and online. The advantage of individualization in a shop is that the process could be better supported by the designers and consequently a more successful production could be guaranteed. In addition, the importance of AR and VR systems for the visualization of the designed product was emphasized in the workshop. It was also stated that the consumers are interested in a realistic representation or even a prototype similar to the final product. On one hand, by implementing the production in a store, it could be ensured that the technology is used correctly and the user experience can be increased. On the other hand, the cost of product development would increase due to an increased need for work and resources. Alternatively, the design process could also be carried out online. In this case, the design process would be possible via an online configurator. A problem with changing the shape could be the calculation-intensive rendering of the representation. Since it is not possible to choose between different previously calculated options, the values would always have to be recalculated. A modern visualization by augmented reality could, however, be realized by using smartphones. In addition, only limited support from the designers would be possible. It can therefore be said that an online implementation would cause lower costs and thus generate a lower price. However, this would be accompanied by much lower levels of usability and user experience.

One of the most important drivers for the success of the design process is the software used to design the product. The software should be as easy to use as possible, as it is used either by the consumers alone or by the consumers together with the designers. At the same time, it should give the users enough possibilities to individualize the product. In addition it is desired that the system manages to check the predicted manufacturability and longevity of a product.

7.4.3 Process

The design processes that were being developed in both the fashion design and the product design group were more acquired more training and expertise for the users than typical mass customization co design processes. Therefore, it is important to determine if the average consumer would be able to use such a configurator. According to the formulated requirements such a configurator, which in this case is actually a generator, would rather be equivalent to a common CAD program, which requires a long training time in order to be used. Such a procedure would therefore only be conceivable for a very specialized group of people. For the remaining users (the majority) one can only speak of very limited usability levels. More feasible is a design process accompanied and guided by designers, as described by the fashion design group. Such an accompanied design process could be implemented both online and in a shop on site.

7.4.4 Product

One of the most important aspects of the system to be defined is the product. In the workshop it was repeatedly stated that a possible product individualization would differ greatly from product to product. Both the process and the requirements for designers, consumers, the technology used and the environment are strongly dependent on which category of a product needs to be designed. An individualization of several product categories via one system is therefore not possible. In addition, it seems difficult for consumers to influence all aesthetic characteristics of the product. If consumers could determine all aesthetic characteristics, the co-design process would be too complicated and therefore not implementable. The space allocated to generate solutions should therefore be expanded, but cannot be completely open.

7.4.5 Outlook

The presented research paper is only a first impulse for a user-centered and consumer-integrating type of production.

Future research will have to find out for which products an extension of classic mass customization offers advantages in terms of ecological and economic sustainability for consumers and manufacturing companies. In addition, product-specific strategies must be developed to make greater individualization possible. One conceivable way would be to develop a toolbox of techniques that would allow individualization of a variety of products and allow companies to select the appropriate techniques for specific products.

In addition, it must be further investigated for which particular products a stronger individualization is desired by consumers.

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Chapter 8
Analysis of the Personal Cars Sustainability in Relation with Their Formalistic Characteristics in Iran

Mohammad Zolfaghari and Seyed Javad Zafarmand

Abstract Considering the importance of personal cars in Iranian users' daily life, this research is aimed to firstly make it clear what level of sustainability the personal passenger vehicles used in Iran have. One of the most important issues that all car makers and designers are concerned about is the formalistic characteristic or stylistic feature of a car. So, the other aim of this research is to understand whether there is any relation between the cars sustainability levels and their formalistic features. In this research, 45 samples of sedan and hatchback cars, which are the most commonly used ones in Iran, are collected. After extracting the indicators of vehicle sustainability from the scholar works, the samples levels of sustainability are calculated. The samples are then analyzed on the basis of their formalistic characteristics. Accordingly, the relation between sustainability levels and the formalistic characteristics of the samples is drawn. The results of this analysis could be effective for developing the design guideline for formalistic features of the sustainable cars.

Keywords Vehicle · Indicator · Sustainability · Formalistic features · Iran

8.1 Introduction

Regarding the theme of this research, on one hand, the formalistic characteristics and stylistic features of cars are very important, since they have a direct effect on the customers' mind. They can give competitive edge to the cars. Many scholar works are done on this issue, such as Hyun et al. (2015). On the other hand, nowadays large number of studies about of cars sustainability and sustainable transportation show the importance of this issue. With high consumption of fossil fuels, there are so many environment impacts derived from cars, such as emissions of HC, CO, NOx and the

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other toxic gases. Mitropoulos and Prevedouros (2013) assessed sustainability for Transportation Vehicles in five urban vehicles. Their assessment revealed that Hybrid Diesel Electric Bus and Hybrid Electric Vehicle have the highest sustainability scores. In transportation, Reisi et al. (2016) explored three urban planning scenarios for Melbourne, Australia in 2030 and their implications for transport sustainability. As the features appearance of the cars reflect value and characteristics, the concerns of this research is to find out, whether there is any relation between sustainability levels and the formalistic features of the cars commonly used in Iran.

8.2 Method

This research is carried out within seven steps shown in Fig. 8.1. At first step, the literatures about vehicle sustainability and formalistic characteristics or stylistic features were reviewed. Then, the cars commonly used in Iran, which mostly included Sedan and Hatchback types, were collected. Majority of the cars used in Iran are produced by two big domestic Iranian makers, Saipa and Iran Khodro (Ikco), and the rest are mostly the assembled Chinese cars or the ones imported from China, Korea and partly the other countries. The samples are introduced in Table 8.1.

In the third step, first, five sustainability dimensions (including Environment, Technology, Energy, Economy and Users) were gathered from the literatures. Then, 15 indicators were determined for vehicle sustainability. The indicators with different units were normalized.

Fig. 8.1 The research outline, steps and process

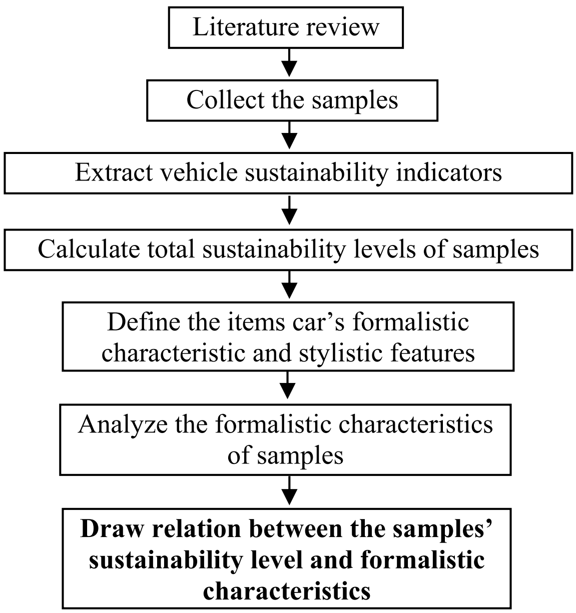

Table 8.1 The samples of commonly used cars in Iran

Car makers	Number of samples	Model
Brilliance	2	H230, H330
Changan	1	Eado
Citroen	1	Xantia
DFM	2	S30, H30
FAW	2	B30, B50
Hyundai	2	I20, Accent
Ikco	5	Dena, Rana, Samand soren, Samand Se, Samand Lx,
Jack	3	J4, J5, J3
Kia	1	Serato
Lifan	3	820, 620, 520
Mazda	1	M-3
MVM	1	315H
Nissan	2	Maxima, Teana
Peugeot	6	508, 207i, 206 Sd, Pars,405,206,
Renault	3	Megan, L90, Sandero
Saipa	5	Pride 132, Tiba, Saina, Rio, Quick,
Toyota	4	Yaris, Camry, Crolla, Prius
Zotye	1	Ario

Each dimension with related indicators was calculated regarding the samples. Finally, the composite or overall dimension (I_{Ov}) was calculated as the combination of five dimensions. With comparison of overall dimension (I_{Ov}) for each car, three levels of sustainability were made. Then, the items of vehicle formalistic characteristic and stylistic features were determined, and accordingly the samples were analyzed on the basis of the resulting items. Using the method of Quantification Theory Type III (QT3), the distributions of formalistic items and the samples were resulted. Using cluster analysis, the samples were grouped on the basis of their formalistic characteristics. Comparing the levels of sustainability through formalistic features of each cluster and each quarter in the resulting distribution graph, finally, the relation between the sustainability levels and the formalistic characteristics or features of samples were determined.

8.3 Framework

8.3.1 Sustainability Dimensions and Indicators

Sustainable indicators, which were first brought up at the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro in 1992, are used as important tools for measuring different aspects of sustainable development (De 1992). Generally, three dimensions of Environment, Society and Economy have been also utilized for sustainability in order to assess transportation sustainability (Freitas and Silva 2012; Haghshenas and Vaziri 2012). A definition supported by international institutions has also the above dimensions (Alonso et al. 2015). Mitropoulos and Prevedouros have divided sustainable transportation vehicles into five dimensions of Environment, Technology, Energy, Economy and Users. In this paper, the authors have used these five dimensions as: vehicles environmental sustainability (I_{Env}), vehicles technological sustainability (I_{Tec}), vehicles energical sustainability (I_{Ene}), vehicles economical sustainability (I_{Eco}), vehicles users' sustainability (I_{Use}) and finally vehicles overall sustainability (I_{Ov}). The process of calculating the overall dimension (I_{Ov}) is shown in Fig. 8.2.

8.3.1.1 Environment

The European Commission defines a healthy environment as "one of the cornerstones of sustainable development… it defines our common identity and thus its preservation for present and future generations" (Wolff 2004). Vehicles emit carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NOx), hydrocarbons (HC), particulate matter (PM), hydrofluorocarbon 134a (HFC-134a), methane (CH_4), and nitrous oxide (N_2O). An understanding of these emissions is needed in discussions

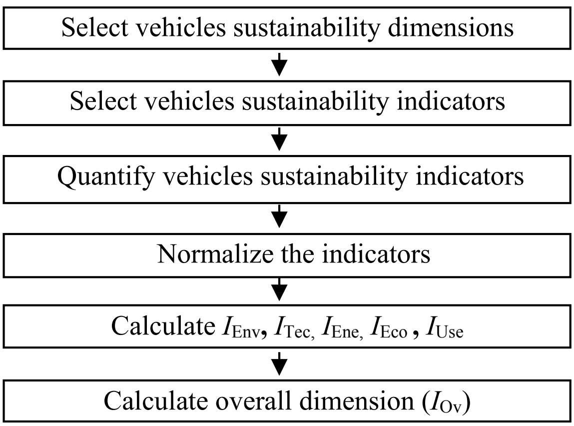

Fig. 8.2 Process of calculating overall dimension (I_{Ov})

of climate change and local air pollution issues (Wallington et al. 2008). These gases are the indicators for environment (Jeon and Amekudzi 2013; Chester and Horvath 2009). The chemistry leading to emissions of HC, CO, and NOx from modern vehicles has been reviewed recently (Wallington et al. 2006). In this research, data of these three gases are collected. Iran Standard and Quality Inspection Company (ISQI) (2019) analyzed these gases for 42 out of 45 sampled vehicles. For the rest of the vehicles, Toyota yaris, Toyota camery and Peugeot 508, there were no data in their company official websites or even emissions test reports. These vehicles have European emission standards 5, 6 so for comparison with others, the least value for each gas, between 42 samples were selected.

8.3.1.2 Technology

Technology development causes using high strength materials while reduction of car weight also optimizing of consumption of non-renewable energy sources. Light weight magnesium and aluminum alloys are finding increased use in automotive applications. The lifecycle CO_2 benefit associates with vehicle weight reduction by material substitution depends on the material (aluminum, magnesium, fiber composites, etc.) (Wallington et al. 2008). The effectiveness of using technology to reduce vehicles pollution and to increase safety and comfort is undeniable, Hybrid vehicles with combination of an electric motor and an internal combustion is one of good examples.

8.3.1.3 Energy

Energy is the major issue for vehicles and directly connected to environment and economy. One of the main concerns of vehicle companies and consumers is vehicle actual consumption. No reduction in energy consumption deprives energy from future generations in long term. In this research information about fuel was taken from the National Iranian Oil Company official website (NIOC) (2019).

8.3.1.4 Economy

It Includes the cost for community, buying, operating, insurance, registration, taxes and maintenance and also the monthly expense for the vehicle parking (Jeon and Amekudzi 2013; Meyer 2016). In this research, the information about car price, insurance and maintenance are collected respectively from an Iranian famous car web site, Bama (2019), Azki (2019) and Digikala (2019).

8.3.1.5 Users

Vehicles with low performance are less attractive for the users and make less satisfaction. All data about customer satisfaction was taken from ISQI official website (2019).

In Table 8.2, the summary of dimensions, indicators definitions, resources and the data for Toyota Yaris which is the highest sustainable car were presented.

8.3.1.6 Indicators Normalization, Calculate Composite Dimension

Transport indicators contain different types of information so there might be some inconsistency in units among indicators. Therefore, before indicators aggregation, it is necessary to transform them to numbers without any dimension. This process is called normalization (Nardo et al. 2005). Indicators whose increasing values have positive impact on sustainability were normalized using Eq. (8.1) and indicators whose increasing values have negative impact on sustainability were normalized using Eq. (8.2) (Krajnc and Glavič 2005).

$$I^{+}_{N,ij} = \frac{I^{+}_{A,ij} - I^{+}_{\min,j}}{I^{+}_{\max,j} - I^{+}_{\min,j}} \tag{8.1}$$

$$I^{-}_{N,ij} = 1 - \frac{I^{-}_{A,ij} - I^{-}_{\min,j}}{I^{-}_{\max,j} - I^{-}_{\min,j}} \tag{8.2}$$

where I_N, normalized indicator I; " $+$ ", for indicator whose increasing value has positive impact on sustainability; " $-$ ", for indicator whose increasing value has negative impact on sustainability; min, minimum value of indicator; max, maximum value of indicator. In order to compare different vehicle sustainability, it is necessary to build a composite or overall dimension to cover environmental, technological, energical, and economical and user's aspects. So sustainability dimensions were combined into a composite sustainability dimension (I_{Ov}) (Gomez-Limon and Riesgo 2008). The calculation of the (I_{Ov}) is a step-by-step procedure of grouping various basic indicators into each sustainability dimension ($I_{\mathrm{S},j}$). Dimensions can be derived as shown in Eq. (8.3) (Krajnc and Glavič 2005).

$$\begin{gathered} I_{s,j} = \sum_{ji}^{n} w_{ji} \cdot I^{+}_{N,ji} + \sum_{ji}^{n} w_{ji} \cdot I^{-}_{N,ji} \\ \sum_{ji}^{n} w_{ji} = 1, \quad w_{ji} \geq 0 \end{gathered} \tag{8.3}$$

Table 8.2 Vehicle sustainability dimensions and indicators

Dimensions	Indicators	Impact	Units	Toyota yaris	Determinants	References
Environment	CO	–	gr/km	0.14	Carbon Monoxide	Jeon and Amekudzi (2013)
	HC	–	gr/km	0.038	Hydrocarbons	
	NOx	–	gr/km	0.006	Nitrogen Oxides	
Technology	Engine power	+	N.m/kg	0.13301	The ratio of max engine torque to vehicle weight	Dom and Ridder (2002)
	Spaced occupied	–	Sq.meters/passenger	1.4534	The ratio of vehicle Length multiples Width to number of passengers	Jeon and Amekudzi (2013)
	Quality Grade	+	Number	4	The result of vehicle static and dynamic evaluation (1 worth, 5 best)	Mitropoulos and Prevedouros (2013)
	Iinitial Quality Study (IQS)	–	PP100 (Problems Per 100 Vehicles)	89	measures problem experienced by new vehicle owners after 90 days of ownership	Alberta (2011)
Energy	Fuel Energy	–	Mjoul/Km	1.8734	Quantification of gasoline fuel energy	Chester and Horvath (2009)
Economy	Vehicle price	–	USD	26,087	The price of the vehicle in Iran	Jeon and Amekudzi (2013)
	Insurance	–	USD	264	Vehicle body insurance price in Iran	Jeon and Amekudzi (2013)
	Maintenance expenditures	–	USD	217.39	Maintenance expenditures for changing vehicle front light	Jeon and Amekudzi (2013)

(continued)

Table 8.2 (continued)

Dimensions	Indicators	Impact	Units	Toyota yaris	Determinants	References
	Fuel price	–	USD/km	0.0295	Vehicle gasoline price for each kilometer	Jeon and Amekudzi (2013)
Users	Service satisfaction	+	Number	767	Satisfaction of vehicle after sales service	Reisi et al. (2014)
	Dissatisfaction ratio	–	Number	0.0147	Satisfaction drop after one year of using vehicle	Reisi et al. (2014)

where $I_{S,j}$ is the sustainability dimension for a group of indicators j (environmental, $j = 1$, technological,$j = 2$, energical, $j = 3$, economical, $j = 4$, users, $j = 5$). W_{ji} is the weight of indicator i for the group of sustainability indicators j and reflects the importance of this indicator in the sustainability assessment of the company. Finally, the sustainability dimensions are combined into I_{Ov} within Eq. (8.4).

$$I_{OV} = \sum_{j}^{n} w_j \cdot I_{s,j} \tag{8.4}$$

In many overall indicators, all variables are given the same weight largely for reasons of simplicity (De 1992). It means that all indicators in the composite have equal importance. Equal weighting is one of the ways for calculating overall indicators (Saisana 2011). In this research the dimensions and indicators weighted equal. Selecting a set of indicators that provides a holistic picture of the considered system is challenging (Castillo and Pitfield 2010). There are several indicators. Having no sufficient date about some of the indicators was the reason for omitting them. In some parts indicator values were replaced with local data. The objective of sustainable urban transport changes with the context, locality, time, and specific knowledge (Castillo and Pitfield 2010).

8.3.1.7 Sustainability Level

After calculating each vehicle overall sustainability dimensions (I_{Ov}) and sorting them, the sustainability level of each vehicle beside the other samples is determined. Sorting from largest to smallest sustainability levels, in order to compare the samples sustainability levels, all samples are divided into 3 groups: high sustainable, middle sustainable and low sustainable.

8.3.2 *Vehicle Formalistic Characteristics*

The vehicle differentiation is often based upon a general understanding of the vehicle form and established relationships between vehicle characteristics (Orsborn et al. 2008). Shape rules, combined with an initial shape, produce a shape grammar that represents the language of the design (Stiny 2006). Shapes themselves can exist as points, lines, planes, volumes, or any combination there of (Stiny 2006). The elements of vehicle characteristics are the most relevant for sufficiently describing the vehicle form (Orsborn et al. 2008).

In this research, the car design characteristics formalistic features (Fig. 8.3 and Table 8.3) were chosen based on Orsborn et al. (2008). However, we have merged and omitted some of the elements of characteristics formalistic features because of just having front and side views of all samples. Each sample has an available high quality photo taken from its company official website in front and side views. For aesthetic analysis of these characteristics, 27 formalistic items were determined. All

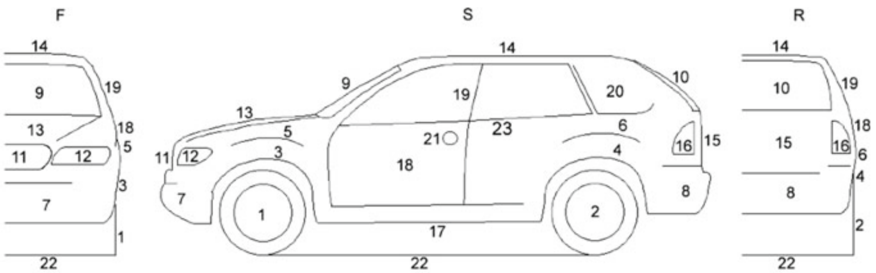

Fig. 8.3 Elements of vehicle characteristic formalistic features, Orsborn et al. (2008)

Table 8.3 Elements of vehicle characteristic and formalistic feature, Orsborn et al. (2008)

Three views: front, side, rear	
(1) Front wheels	(13) Hood
(2) Rear wheels	(14) Roof
(3) Front wheel well	(15) Trunk
(4) Rear wheel well	(16) Taillight
(5) Front fender	(17) Rocker
(6) Rear fender	(18) Door
(7) Front bumper	(19) Front side window
(8) Rear bumper	(20) Rear side window
(9) Front windshield	(21) Door handle
(10) Rear windshield	(22) Ground
(11) Grill	(23) Belt line
(12) Headlight	

Table 8.4 Items used for formalistic analysis of samples

Elements	Items	Elements	Items
Front silhouette	A1: Vertical lines	Front bumper	F1: Horizontal lines
	A2: Corners	Front bumper grille	G1: Fog light shape
	A3: Total shape		G2: Size
Front window	B1: Height		G3: Vertical lines
	B2: Total shape	Side Window	H1: Vertical angle
	B3: Corners		H2: Height
Hood	C1: Horizontal lines	Side Front Fender	I1: Curvature
	C2: Vertical lines		I2: Length
	C3: Total shape	Side Door	J1: Vertical angle
Front grille	D1: Total shape		J2: Belt line angle
	D2: Size		
	D3: Corners		J3: Corners
Headlight	E1: Size		
	E2: Horizontal lines	Roof	K1: Curvature
	E3: Vertical lines		

vehicles Elements characteristics formalistic features and items of this research are introduced and shown in Table 8.4.

The belt line, which starts at the bottom of the A-pillar and runs along the bottom of the side windows to the trunk, is an important characteristic. There is no specific curve for the belt line, but it will be built using a combination of the related characteristics: the hood, side windows, and trunk.

8.4 Result

8.4.1 Samples Overall Sustainability Levels

Using Eqs. (8.1) to (8.4), the overall sustainability (I_{Ov}) for all samples are calculated and divided into 3 levels. As Fig. 8.4 shows 26.66% of samples are in high sustainable level, 53.33% are in middle sustainable level and 20% are in low sustainable level. The highest sustainable car is Toyota Yaris and the lowest sustainable car is Nissan Maxima.

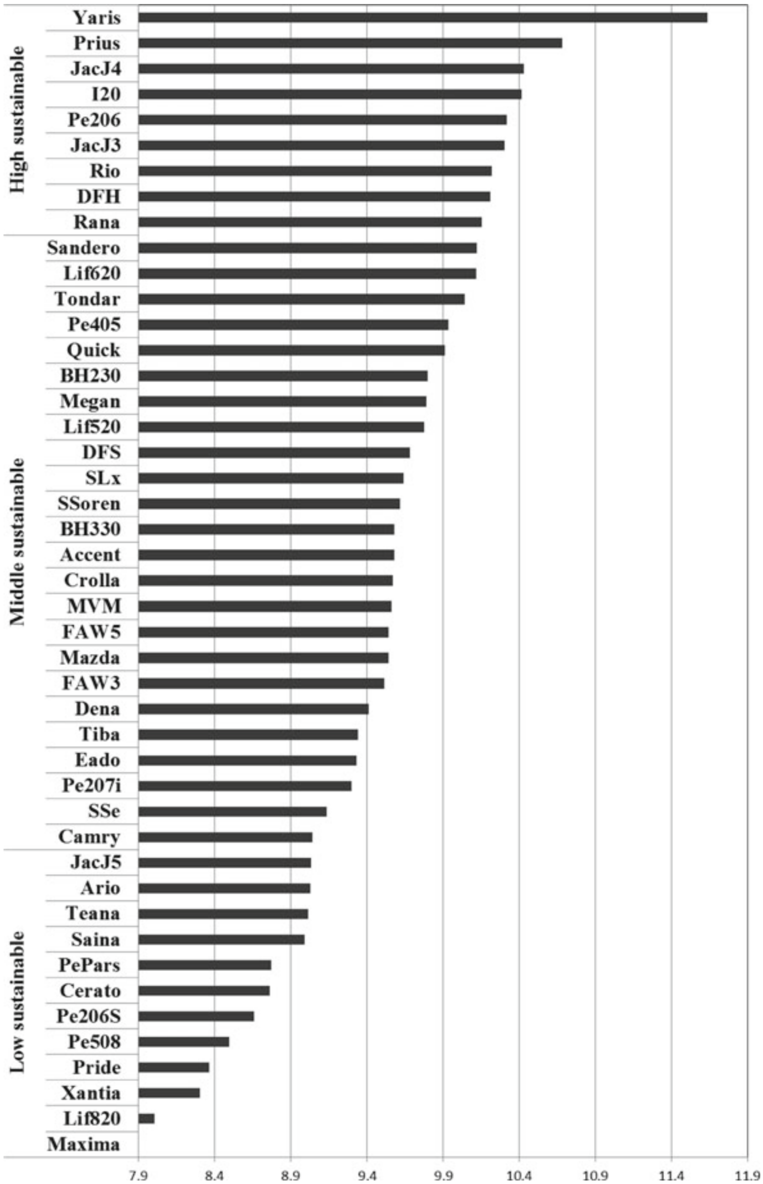

Fig. 8.4 The sustainability levels of the samples

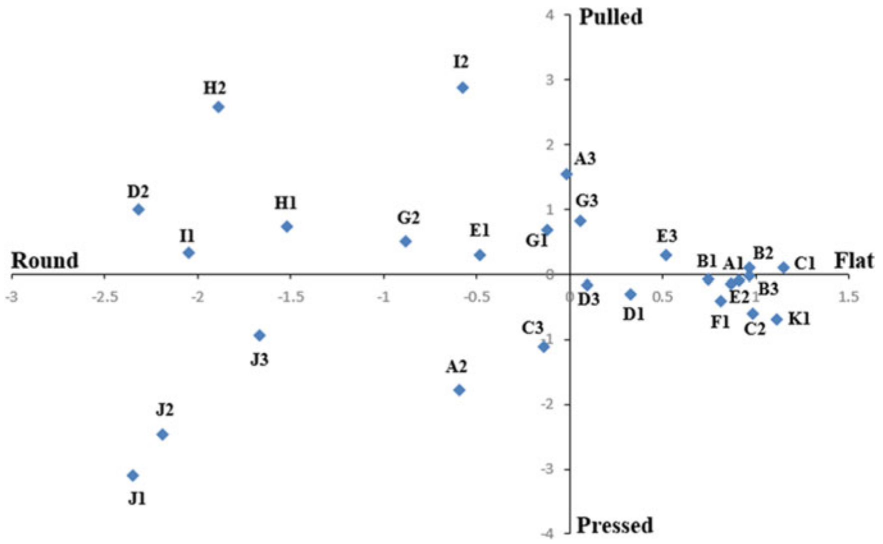

Fig. 8.5 Distribution of the formalistic items

8.4.2 *Formalistic Items Distribution*

The overall output distribution graph of formalistic items is shown in Fig. 8.5. The directions of the two axis of X and Y are respectively named Round-Flat and Pressed-Pulled. These given names are based on the context and distribution of the items in the graph. Also this analysis was done for samples to show the distribution of samples according to characteristic formalistic items.

8.4.3 *Samples Formalistic Distribution and Clusters*

To classify the samples according to their formalistic features, the linkage distance across fusion steps may help (Milligan and Cooper 1985). The axis directions have been named Round-Flat and Pressed-Pulled according to the distribution of formalistic items. In a same formalistic distribution of the cars, the names of axes suggested by Abdulrahman et al. are "round-boxy" and "heap-disperse" (Rahman et al. 2013). As the formalistic items and our given names to the axes are so close to the above-mentioned research, the same names with some changes for X and Y axes are used in these research: Round Face—Boxy Face and Heap—Disperse.

The chosen cut-off for the clustering algorithm has yielded five clusters Fig. 8.6, which marked from CL1 to CL5. The cut-off line is made to have meaningful groupings for understanding of the relationship between various vehicles.

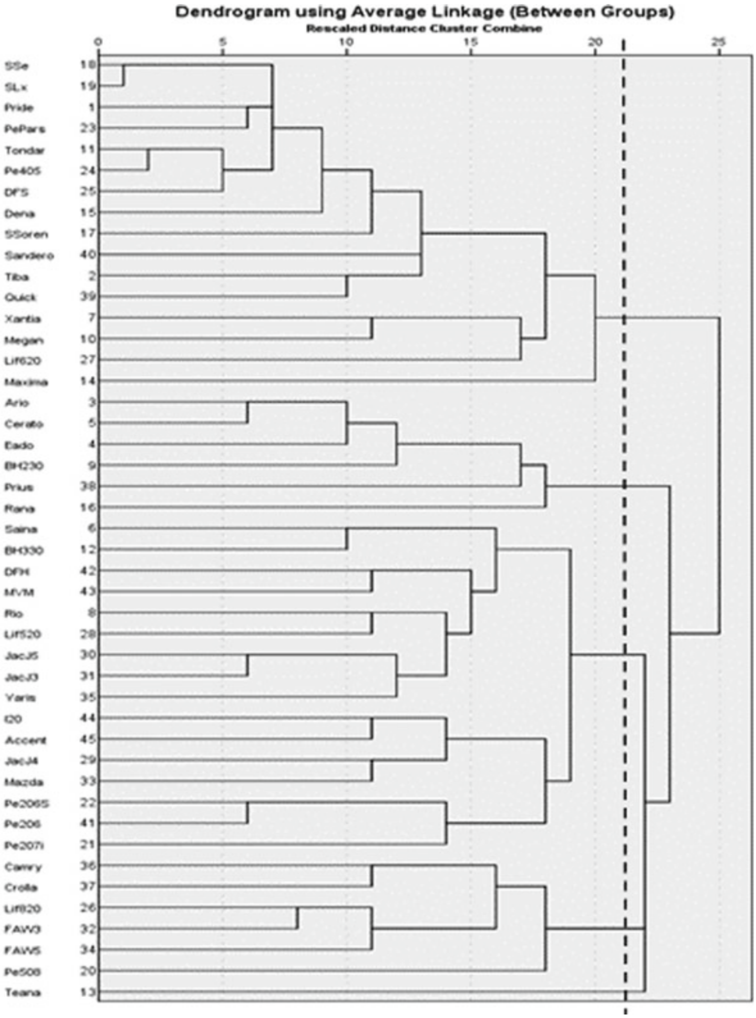

Fig. 8.6 Clustering algorithm of the samples

Also relative frequency of each formalistic items in each cluster were determined, high range of relative frequency formalistic items in a cluster, shows the effects of these items in cluster. Then the vehicles sustainability relevant frequencies in each quarter were determined. Finally, the relation between the samples sustainability with characteristic formalistic features were analyzed.

Figure 8.7 shows the output distribution of samples into the four quarters of graph. Each quarter based on the distribution of cars and its formalistic features, is expressed.

Quarter 1 (Q1) or disperse- boxy face area contains the samples showing power in this series of cars that are robust. In Quarter 2 (Q2) or round face-disperse area the samples are volumetric. In Quarter 3 (Q3) or round face-heap area the samples

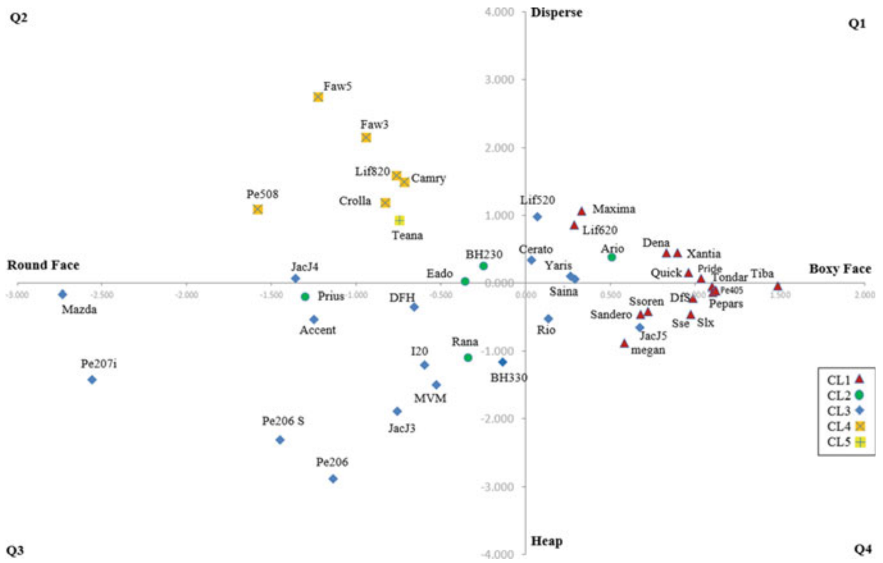

Fig. 8.7 Distribution graph of the samples based on their formalistic characteristics

are dynamic and small. But, in Quarter 4 (Q4) or heap-boxy face area, the samples look boxy.

The main formalistic characters of the resulting clusters are “front window” and “hood” in CL1, Headlight and Side Window in CL2, Front bumper Grille in CL3, and Side Front Fender and Front Bumper Grille in CL4. As there is just one sample in CL5, it can be characterized with that sample.

8.4.4 Sustainability Levels of Clusters and Quarters

Here, for each cluster, the relative frequency of its belonging samples laid in each level of sustainability is determined. The relative frequency of levels of sustainability in each cluster and each quarter of the distribution graph are shown in Tables 8.5 and 8.6.

The distribution of samples through the clusters shows that CL3 has the highest numbers of high sustainability. In this cluster the characteristic formalistic item is big and curved Front bumper Grille. According to the distribution of high sustainable cars in quarters, the highest numbers of high sustainable cars are in Q3, as mentioned before this quarter is named dynamic and small. So half of high sustainable cars between commonly used car in Iranian market have dynamic and small image with big and curved front bumper grill, another features are high angle with the horizon of belt line and pressed side front fender that make cars look more aerodynamic, these cars have the minimum area and height between other samples. CL4 has the

Table 8.5 Relative frequency of samples sustainability levels in each cluster

Cluster	Percentage in samples (%)	Sustainability in clusters		
		High (%)	Middle (%)	Low (%)
CL1	35.56	18.8	56.3	25
CL2	13.33	33.3	50	16.7
CL3	35.56	43.8	43.8	12.5
CL4	13.33	0	66.7	33.3
CL5	2.22	0	100	0

Table 8.6 Relative frequency of samples sustainability levels in each quarter

Quarter	Percentage in samples (%)	Sustainability in quarter		
		High (%)	Middle (%)	Low (%)
Q1	24.44	18.2	36.4	45.5
Q2	22.22	10.0	70.0	20.0
Q3	26.67	50.0	41.7	8.3
Q4	26.67	25.0	66.7	8.3

highest numbers of middle sustainable cars. The cluster formalistic items are pulled Side Front Fender and big Front Bumper Grille. Distribution of middle sustainable cars through Q2 shows that the majority of middle sustainable cars in Iranian market are volumetric.

Finally, comparing the characteristic features in CL1 and Q1, majority of low sustainable cars have flat window and hood with boxy face that look less aerodynamic but robust.

8.5 Conclusion

Majority of high sustainable cars in Iranian market are produced or assembled in Iranian car factories and few numbers are imported from other countries. Producing or assembling cars with less fossil fuel consumption, would be effective to change the position of some low and middle sustainable cars to high sustainable in Iranian market. Causes of the Iranian car factories do not have any hybrid and electric cars production and modern technology to make more aerodynamic car body shape, majority of cars in this market have no chance to be in high sustainable level. In this market users' choices are so limited, some economic and political issues are the main reasons for having heavy Customs tariffs which don't let the users import cars from other countries. The cars formalistic features are so important for customers. According to the findings, half of high sustainable cars in Iran have dynamic and small form, big and curved front bumper grill, high angle with the horizon of belt line and pressed side front fender that make these cars look more aerodynamic, having minimum area and height of these cars between the others are important advantages for urban transportation and parking problems in large cities. Majority of samples are middle sustainable cars which their notable characteristic is volumetric look, these samples also have round face. Low sustainable samples have old platform of body design as well as the flat front window that makes them look less aerodynamic. The findings of this research can be applied to illustrate some design guidelines for stylistic features and formalistic characters of sustainable cars.

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Part II
Sustainable Consumption and Production

Chapter 9
Enhancing Role and Participation of Industry and Community for Sustainable E-Waste Recovery for Sustainable Consumption and Production (SCP): Case Study Kuala Lumpur Malaysia

Ahmad Fariz Mohamed and Muhammad Izzat Rasnan

Abstract Malaysia rapid development has benefitted its people while continuously gain better quality of life and are now demanding modern and high technology lifestyle. For example, the subscription of hand phone and smartphone in 2004 was 12.3 million and increased to 42.3 million, while population of Malaysia in 2004 was 23,522,480 and in 2017 the population increased to 32,022,600. Life style and rapid growth of electronic products consumptions accelerated the generation of E-waste in Malaysia. The need to manage E-waste in a sustainable manner has created many challenges. One of the challenges is to educate and make individual or community to be more responsible and participate for sustainable E-waste management in Malaysia. A sustainable E-waste recovery is important for sustainable consumption and production (SCP) of electronic products. For this purpose a study was conducted to understand the readiness of key stakeholders to support for efficient E-waste recovery in Kuala Lumpur City. The study has identified key factors important for E-waste recovery to ensure sustainable production and consumption of electronic products. Survey was conducted with selected Kuala Lumpur community asking their understanding of E-waste and how they handle six types of E-waste namely televisions (CRT and LED/LCD), refrigerators, washing machines, air-conditioners and desktop computers. Almost 61% of the respondents understand the E-waste definition, and aware of E-waste impacts towards the environment and human's health. The practice of E-waste recovery was found encouraging for the six E-wastes. The number of respondents recover or recycle LED/LCD TV (43.3%), CRT TV (50.8%), refrigerators (45.8%), washing machines (48.4%), air-conditioners (49.1%) and desktop computer (50.8%). Material flow analyses findings shows that there is a weakness in collection system, retailers capability are underutilized, household attitude lead to poor collections and low amount of household E-waste treated. While the strength

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of the existing E-waste recovery is a strong scrap collector's influence and established E-waste recycling industry within and outside Kuala Lumpur. Findings from this study shows that there is a need to enhance participation and the practice of E-waste recovery especially among the community and consumers. Mechanisms and system which improve the existing systems and mechanisms for E-waste recovery in supporting SCP will requires industry commitment and participation with strong support from the consumers and government agencies.

Keywords E-waste · Community · Industry · Participation · System · Recovery

9.1 Introduction

Malaysia is one of the country which has embarked on industrialization as it economic growth engine since 1960s. Transition from agricultural and raw material industries to manufacturing industry start in the early 1960s (Mohamed 2014). The manufacturing industry show a steady growth and has contributed Gross Output Value from RM 1.2 Billion (USD 280 Million) in 1959 to RM 1.14 Trillion (USD 270 Billion) in 2015. And in 2018 the Gross Output value increased to 1.27 Trillion (USD 300 Billion) in 2018 (Department of Statistics (DOS) 2017). In addition this industry has created a total of 60,570 jobs in 1959 and increased to 2.1 million jobs in 2015 (Department of Statistics (DOS) 2017). As of 2017, 2.2 million jobs were created from the manufacturing industry. The increasing of the contribution from manufacturing industry in Malaysia come from projects that are high value and high growth industries. One of the high values and high growth industries in Malaysia is the electrical and electronic industry. The electrical & electronics (E&E) industry is the leading sector in Malaysia's manufacturing sector, contributing significantly to the country's manufacturing output (26.94%), exports (48.7%) and employment (32.5%). In 2010, the gross output of the industry totaled US$50.94 billion, exports amounted to US$75.7 billion and created employment opportunities for 325,696 people. The electrical and electronic industry maintain its leads where in 2017, the industry was the country's largest export earner, totaling RM343 billion and accounting for 36.7 per cent of the total value of exports (MIDA 2019). Taking examples of key consumer electronic products, the trend shows an increasing trends where television production increased from 107,445 unit in 1975 to 13,163,257 in 2010. The room air-conditioners also show increasing trends from 111,631 in 1977 to 2,593,647 in 2010. Advancement of information and communication technology (ICT) have driven the technological innovation and the increasing demand for electronic products that support this technology. Mobile phones is one the main products which play important role for the advancement of ICT in the world and Malaysia. These scenario has driven the sales and use of mobile phones in Malaysia. In 2014, there were 43,248,000 mobile phone subscriptions with a penetration rate of 144.2 per 100 inhabitants, a high penetration for the subscriber base to be treated as a virtual frame of individuals. Then in 2017, there were 42.3 million mobile-cellular subscriptions with a penetration rate of 131.2% to a population of 32.3 million. While in 2016, there were 28.5 million mobile broadband subscriptions compared to 2.5 million fixed broadband subscriptions (Malaysian Communications and Multimedia Commission 2015, 2018). The increasing trends of productions and consumption illustrate that the demands for electronic products increased significantly, especially when the products were made to be affordable and easy to use and access.

The effects of the increasing demand of these electronic products to sustainable consumption and production (SCP) is critical. The positive increasing demand will drive the growth of the industry in future. However there are critical concern on the part of electronic wastes generation and unsustainable consumption of natural resources to support to the need of the electronic industrial growth. There is a need to understand the demand of resources and materials for electronic and electrical industry production, which affects the natural resources supply. In addition there is negative impact from the extraction of natural resources for electronic products raw materials. For example rare earth mining operation for rare earth metals are used to make all kinds of high-tech consumer products. The three main process, mining, refining and disposal have been found negatively impacted the environment and human health (Humsa and Srivastava 2015; Rashid et al. 2018). In addition to the raw materials production impacts, the consumer consumption lead to increasing E-waste generation. Malaysian consumers for example generated 706,295 metric ton of E-waste in 2010, and the number is estimated to increase to 1,119,115 metric ton in 2020. With the large amount of E-waste generated by Malaysian consumers, there is a need to manage these wastes in a sustainable manner. Thus it is important to place an emphasis to need for E-waste recovery which play an important role for sustainable consumption and production (John et al. 2010).

The E-waste recovery in Malaysia is still at infant stage. There are many aspect that needs to be put in place before E-waste recovery in Malaysia able to be effective to support sustainable consumption and production requirements. For the start Malaysian government through the Department of Environment has embarked on a specific program to manage E-waste in a sustainable manner (Rasnan et al. 2016). This program come equipped with legislation and specific strategy. However this is not enough. Government agency alone would not make the E-waste recovery sustainable in Malaysia. There is a need to make all the key stakeholders understand the electronic products recyclable requirements and capability. The key stakeholders are the community and industry in addition to government agencies. At the current situation, participation of community and industry to recover E-waste through recycling, reuse and reduce is still not encouraging. There is a critical issue of community and industry lack of participation for E-waste recovery, which will affect the efficiency of sustainable consumption and production, especially for electronic industry. The role of these two groups is important to ensure the material flows of E-waste recovery is efficient and sustainable, which important for sustainable consumption and production sustainability (Mohamed 2013). However to ensure they play the role effectively, these groups still require government agencies intervention, which mostly done through education and awareness program.

The study was conducted to assess how important the role of the community and industry for E-waste recovery in supporting the needs for sustainable consumption and production. The key question in this study is, what are the key factors important for E-waste recovery to ensure sustainable production and consumption of electronic products? To answer this question, the study was conducted in the Kuala Lumpur City. The community and industry in Kuala Lumpur City was chosen as it has a dynamic population and industry which play important role for E-waste recovery is found active. The factors identified were analyzed and the connection of the factors in reference to E-waste recovery and sustainable consumption and production was discussed.

9.2 Methods

Survey was conducted focusing on consumers, collectors, and recyclers to understand their role in E-waste recovery and to determine factors which will contribute to a sustainable E-waste recovery for sustainable production and consumption of electronic products. The sample of respondents of consumers for this study was from Kuala Lumpur city. Specifically two residential areas were sampled. They are PPR Laksamana Jalan Peel (WPKL-12) and Kampung Malaysia (WPKL-15) from 17 waste management zones of Kuala Lumpur. The selection of these sampling area is due to their involvement in UN Local Agenda 21 initiative 'Best Practices of Waste Management' conducted by Kuala Lumpur City Hall. Under this program, the local communities were exposed with sustainable waste management projects such as waste minimization, segregation, and composting. The questions ask to respondents are based on four themes. Themes 1 focus on the respondents background such education level, monthly incomes, and household types. Themes 2 focus on E-waste awareness. Themes 3 on electronic products ownership and E-waste disposal practices, and themes 4 focus on perception and opinion regarding existing e-waste management. The total number of the consumers respondents participated in the survey are 120 respondents. As for the collectors and recyclers, Three DOE-registered E-waste contractors, waste concessionaire for Kuala Lumpur, and one charity organization involved with E-waste collection were interviewed through meetings or phone interviews. These four respondents were chosen as they are licensed collectors and recyclers.

Analyses of material flow (MFA) was conducted to understand the flow of E-waste in Kuala Lumpur and to determine factors which will contribute sustainable E-waste recovery for sustainable production and consumption of electronic products. MFA enables the identification of weaknesses in the E-waste recovery system. Understanding the flow of wastes from generation to recovery or disposals is important to determine key factors which will affect the E-waste recovery. The targeted substances in this study are determined based on the following criteria: (1) household E-waste that is commonly used; (2) readily available data; (3) established recycling activities. Based on these conditions, six items have been identified. They were televisions (CRT and LED/LCD), refrigerators, washing machines, air-conditioners, and desktop computers in the current system, which can serve as a guide for improvement measures.

9.3 Results and Discussion

There are 146 E-waste recovery facilities in Malaysia with the total capacity to handle more than 24,000 metric ton of E-waste per month licensed by the Department of Environment Malaysia (DoE). From this, 128 are partial recovery, small and medium size operators engaged in physical or manual segregation of E-wastes for further processing. 18 full recovery facilities which can process the E-wastes to recover the precious metals (Department of Environment (DOE) 2015). The overall picture of E-waste generation for Malaysia was illustrated in Table 9.1a, c. While for the

Table 9.1 Projection of E-waste in Malaysia, 2010–2020

Year	TVs	PCs	Rechargeable batteries	Total (Tonnes)
a Projection of E-waste in Malaysia, 2010–2020				
2010	236,817	222,820	125	459,762
2011	206,739	256,981	146	463,866
2012	215,176	294,339	169	509,684
2013	213,750	328,479	191	542,420
2014	242,320	379,142	211	621,673
2015	261,837	418,897	229	680,963
2016	249,030	457,581	242	706,853
2017	215,387	500,212	253	715,852
2018	217,758	546,937	262	764,957
2019	220,712	592,359	269	813,340
2020	224,226	608,191	275	832,692

Year	Cell Phones	Refrigerators	Total (Tonnes)
b Projection of E-waste in Malaysia, 2010–2020			
2010	795	73,457	74,252
2011	1,030	60,900	61,930
2012	1,276	59,057	60,333
2013	1,514	60,889	62,403
2014	1,726	62,554	64,280
2015	1,892	64,100	65,992
2016	2,004	65,756	67,760

(continued)

Table 9.1 (continued)

Year	Cell Phones	Refrigerators	Total (Tonnes)
2017	2,078	67,465	69,543
2018	2,136	69,219	71,355
2019	2,192	71,019	73,211
2020	2,249	72,866	75,115

Year	Air Conditions	Washing Machines	Total (Tonnes)
c Projection of E-waste in Malaysia, 2010–2020			
2010	1,42,982	29,299	1,72,281
2011	1,39,516	29,710	1,69,226
2012	1,40,935	29,633	1,70,568
2013	1,45,559	29,497	1,75,056
2014	1,48,226	31,205	1,79,431
2015	1,46,878	33,153	1,80,031
2016	1,43,483	37,805	1,81,288
2017	1,40,810	49,818	1,90,628
2018	1,40,501	54,362	1,94,863
2019	1,42,402	59,847	2,02,249
2020	1,45,495	65,853	2,11,348

Source (Department of Environment, Malaysia 2018)

Kuala Lumpur City, the estimated E-waste Generation from 2008 to 2013 is shown in Table 9.2. The E-waste generation shows an incremental trends each year, which shows that it requires intervention for recovery to support sustainable consumption and production needs.

Based on the responses obtained from the survey, it can be surmised that the number of Kuala Lumpur's households who knows about E-waste and aware about its consequences exceed their ignorant counterparts (refer to Fig. 9.1). In terms of understanding of E-waste definition, it is discovered that most households practically understand what are the electrical and electronic wastes is. However, when it comes

Table 9.2 Total projected number of household E-waste in Kuala Lumpur 2008–2013 (Units)

Type of E-waste	Total units
Television	356,664
Air-Condition	356,664
Washing Machine	121,252
Refrigerator	334,591
Desktop Computer	351,713

Source Department of Statistics (DOS) (2013), Huisman et al. (2008)

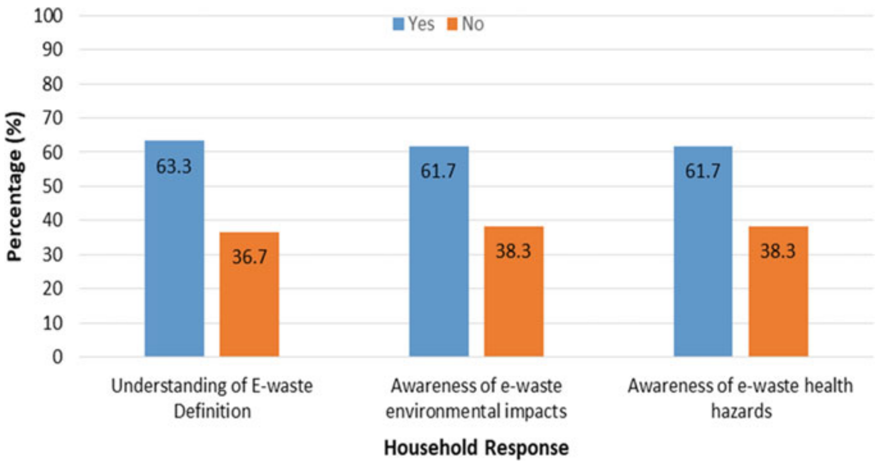

Fig. 9.1 Households' E-waste knowledge and awareness

to the terminology of 'E-waste,' they are finding it difficult as it can be considered as a technical jargon in the field of waste management. Besides, most of the respondents claimed that they are aware of E-waste impacts towards the environment and human's health. However in term of percentage the knowledge and awareness among Households who participated in the survey shows an encouraging numbers as more than 60% of them say yes to the three questions.

Findings from survey, also shows that there are variances in E-waste disposal practices among the households that are caused by multiple factors (Fig. 9.2). Most households prefer to sell their electrical appliances to scrap collectors due to primarily economic reason. The number of respondents recover or recycle LED/LCD TV (43.3%), CRT TV (50.8%), refrigerators (45.8%), washing machines (48.4%), air-conditioners (49.1%) and desktop computer (50.8%). The second most opt action in handling E-waste is storage. As explained by Kalana (2010), Afroz et al. (2013), the practice of storing is popular among households due to sentimental reasons, and also biased estimations of E-waste values that are based on its original prices. Meanwhile, the third most common action is discard. This is by far the most convenient method, especially for the 40% of households that lacks the understanding and awareness of E-waste hazards. On the other end, only a small portion of households (3–7%) claimed that they would donate or recycle their E-waste; which can be explained by the bulky nature of the inquired appliances that are difficult to move and transfer. The least popular action is returning E-waste upon the delivery of new appliances to retailers. This can be attributed to the absence of regulation like the Extended Producers Responsibility (EPR), or lack of monetary incentives among retailers and producers to conduct such scheme.

From the interviews with partial recyclers, it is found that most of E-waste that they treat, 70–80%, originates from government institutions and businesses. This is because of the high volume of E-waste turnover rate during hardware updates such as

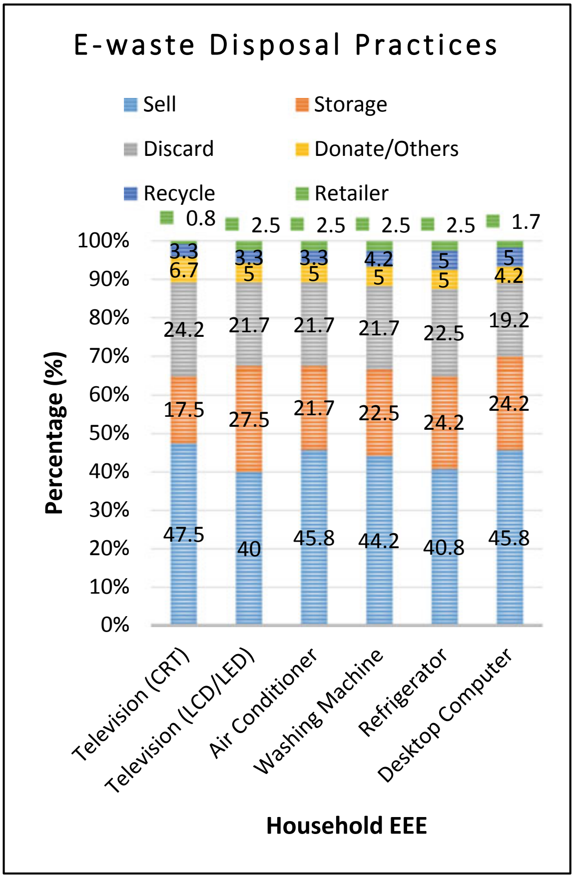

Fig. 9.2 Kuala Lumpur City Households' E-waste disposal practices

computers and air-conditioners, which made collection procedures more systematic and profitable. Only about 20–30% of E-waste obtained by partial recyclers are from households, mostly through formal channels and occasional awareness campaigns. Refer to Fig. 9.1, Tables 9.1 and 9.2, there is a critical needs to enhance community role towards effective E-wastes recovery activities for SCP requirements. Their role could be enhance by understanding the material flow of E-waste from households to recovery and disposals (Springer International Publishing AG 2018).

Material flow analyses (MFA) was conducted with the system boundary, which covers processes of E-waste management in the city of Kuala Lumpur. As can be seen on Fig. 9.3 below, it begins from the collection of E-waste from households, and end with the material recovery facilities and landfill. In the MFA diagram (Fig. 9.3), there are three key tiers that important for E-waste recovery in Kuala Lumpur city. The first tier of the MFA is essentially the representation of household disposal practices. Tier 1 illustrated the movement of E-waste to six receiver, namely scrap collector, waste collector, donation or charity, recycling center, retailer and storage. Majority of the

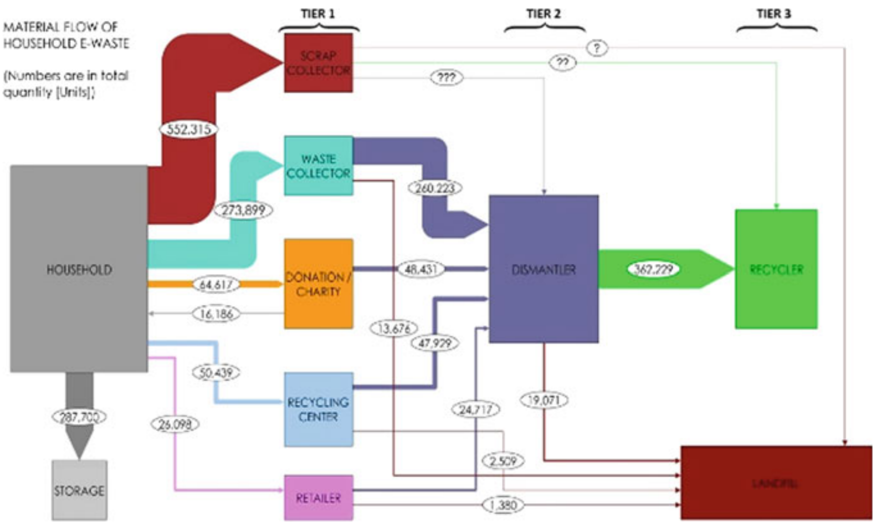

Fig. 9.3 Material flow of household E-waste in Kuala Lumpur

household E-waste were send to scrap collectors and waste collectors. In the second tier, E-waste dismantling take place. It is found that majority of formally collected household E-waste (through waste concessionaire, charity bodies, recycling centers, and retailers) are sent to partial E-waste recyclers, with authorization by the DoE. For the dismantling processes, the E-waste is broken down into smaller parts in accordance with their properties and recyclability. In the third tier, the full-recyclers received dismantled E-waste for material recovery and hazardous waste treatment. The dismantled parts are treated and processed into secondary materials.

The material flow analyses help to determine the key factors important for E-waste recovery to ensure sustainable production and consumption of electrical and electronic products. The MFA helps to determine action on how to enhance role and participation of consumers, industry and government agency for effective and sustainable E-waste recovery for SCP needs. The key findings from this study which affected the community role and participation are related to level of knowledge, perception and culture. There still high number of consumers with absence of knowledge on how to dispose E-waste properly. The knowledge on how to dispose also related to the design of the products. There still many electronic and electrical products which are not suitable for recycling. Thus the producers must design and manufacture products which are easily recovered and recycled. Study also shows that there are practice of culture, where the possibility of E-waste being restored and use in future. However after certain times, at the end the product become E-waste. There are also the perception by consumers that reluctant to dispose their E-waste as they were bought at high prices, especially for the large household appliances. The perception of products value affect the understanding of products depreciation values with times, which lead to denial of decreasing products value and storage of products. Insufficient infrastructure for temporary storage and inefficient collection system also affect the role and participation of consumers. As the E-waste generation growth rapidly, the needs for effective infrastructure and system is critical especially in the city.

9.4 Conclusion

The study was conducted to understand the readiness of all key stakeholders to support for efficient E-waste recovery in Kuala Lumpur. E-waste recovery is important for sustainable production and consumption of electronic products, especially in Kuala Lumpur and Malaysia. Consumers of Kuala Lumpur City are ready to participate actively for E-waste recovery, but will require certain of aspects of supports from the industry and government agencies. The study also determined key factors important for E-waste recovery to ensure sustainable production and consumption of electronic products. The key factors are to enhance participation and the practice of E-waste recovery especially among the community and consumers. Mechanisms and system which improve the existing systems and mechanisms for E-waste recovery in supporting SCP will requires industry commitment and participation with strong support from the consumers and government agencies. Due to the nature of modern manufacturing and global supply chain, raw materials for production are sourced from all over the world. It is important to have an alternative resources where, recycling industry are ready to come in for this task. Thus the E-waste recovery system is important, and consumers' role and participation help to ensure that the materials were channel back to the manufacturing system. As the E-waste generation grow each year and estimated RM12 to 15 million worth of E-waste produced in Kuala Lumpur city annually, it will needs efficient systems with strong support participation of key stakeholders especially the consumers. However to enhance community participation requires collection system supported with infrastructure and effective system by government agencies and industry along with continuous education and awareness program (Kasavan et al. 2019). The MFA conducted help to determine the role of consumers, collectors, recyclers and retailers, as well understanding how to develop and operate the system efficiently.

This findings shows that the consumers and industry are key stakeholders for E-wastes recovery to support SCP initiatives in Malaysia. Malaysia government has establish The National Sustainable Consumption and Production (SCP) Blueprint (2016–2030), where it has 10 pathways to achieve SCP in Malaysia 2016. The participations and active role of consumers and industry was clearly stated in the blueprint (Adham et al. 2013). Therefore the Malaysian policy on SCP acknowledge the importance of consumers and industry role and participations to achieve the National SCP targets. Thus the findings of this study shows that the process of education, awareness and creation of responsibility with commitment for these two stakeholders are now is a ongoing process. Thus will support towards achievement of SCP Malaysia targets by 2030.

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Chapter 10
Understanding of Individuals' Intention Toward Car Sharing Usage in the Southeast-Asia Region: From University Students in Thailand and Indonesia

Yoon-Young Chun, Mitsutaka Matsumoto, and Kiyotaka Tahara

Abstract Increased car ownership-levels in Southeast-Asian developing countries may lead to extensive environmental and social issues, thus unsustainable development. Car sharing is one promising approach to change the way people use cars. Socio-demographic, psychological, or infrastructural attributes (variables) are influential factors of transport mode choice and may determine the adoption and diffusion of car sharing services in the Southeast-Asia region. In this article, we focus on several factors that might affect the decision toward car sharing use in the Southeast-Asia region, where car sharing is so far effectively non-existent. This paper presents the result of a preparatory study conducting comprehensive literature reviews and semi-structured interviews performed in Thailand and Indonesia to understand the potentially influential factors for car sharing adoption in the Southeast-Asia region. Based on the preparatory study, this paper also formulates the hypotheses that the identified factors positively (or negatively) influence the car sharing adoption intention. It is hoped that these hypotheses will be further tested by statistical analysis to investigate the interplay among the factors, and car sharing decisions of Southeast-Asian residents. The findings will give us implications for business opportunities and policies to promote environmentally-sustainable car sharing services in the Southeast-Asia region.

Keywords Sharing economy · Socio-demographic factor · Psychological factor · Infrastructural factor · Sustainable consumption

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10.1 Introduction

By 2050, 68% of the world's population will live in urban areas compared to 2018 when 55% lived in urban areas (United Nations (UN) 2018). Urbanization provides us economic, cultural and societal benefits, but the rapid often unplanned urbanization leaves us substantial tasks to be resolved in cities. For instance, the increase in the urban population will create new demand for more efficient and sustainable transport (International Transport Forum (ITF) 2017).

Car ownership level is increasing in many developing countries. Within the OECD countries, projected growth in vehicle ownership is relatively slow, but for the non-OECD countries, the rates of growth are forecast to be much faster (Dargay et al. 2007; Shihab-Eldin et al. 2004; World Business Council for Sustainable Development 2004). The upgrade process where current motocycle owners are buying cars is a particularly prevalent phenomenon in Southeast-Asian developing countries (Belgiawan et al. 2016). Profoundly increased car ownership may lead to extensive environmental and social issues, thus unsustainable development. Thus, understanding the future car travel behavior of individuals in Southeast-Asian developing countries will be a timely theme to us at a time when these countries are witnessing rapid growth and transformation in the social, economic, and transportation-related contexts.

Car sharing is the service that provides users with access to a fleet of vehicles on an hourly basis (Burkhardt and Millard-Ball 2006). This allows individuals to enjoy the benefits of private vehicle use with fewer costs, but without responsibilities of car ownership (Costain et al. 2012). Many cities and transportation planners have considered car sharing schemes as one promising solution of designing their societies to help meet growing travel demand while lessening automobile dependence.

While many studies have focused on individuals' perception, motives, or behavior intention involved in car sharing usage for developed countries, a consumer perspective is largely unexplored for Southeast-Asian countries. The objective of this study is to explore the factors that might affect the decision on car sharing adoption in Southeast-Asian developing countries, where car sharing is so far effectively non-existent. This study, based on comprehensive literature reviews and semi-structured interviews with university students in Thailand and Indonesia, attempted to specify critical factors among relevant ones and to formulate the hypotheses that the factors influence the car sharing adoption intention. The findings from this preparatory study can be served as a basis for developing a model that uncovers the correlations among the factors to explain travel behavior related to car sharing adoption, especially in Southeast-Asian countries.

10.2 Materials and Methods

To understand influential factors that potentially contribute to the decision of car sharing adoption intention, this preparatory study was conducted by two main pillars.

- Literature reviews on previous case studies of car sharing: the scope of the reviews targeted mainly car sharing cases but was not limited to them. The topics also covered car ownership decision to generally understand the factors affecting individuals' car travel behavior, which can be (directly/indirectly) linked to car sharing adoption.
- The survey using a semi-structured interview was performed in Thailand and Indonesia, where car sharing is so far virtually unknown and effectively non-existent.

10.2.1 Literature Review Analysis

The literature review was conducted using the Scopus database, which contains articles from all major journals dealing with the transportation, green and sustainable science and technology fields, including scientific refereed journals and conference proceedings, and project reports as a source for the car sharing literature. The study restricted the search to the papers dated from 2001 to the present, 2018 (last extraction of the database, October 2018). The search of the papers was structured in two main pillars. First, multiple keywords were used to investigate the studies identifying factors to the adoption of car sharing: "car sharing", "car sharing adoption", and "car ownership". The terms were first singularly and were then combined using the AND operator in association with the single keywords "user behavior", "factor". After a screening the analysis found and selected 44 references, and these were the basis for a comprehensive understanding of the factors affecting car sharing adoption decisions and related aspects of car ownership (see Sect. 10.3).

10.2.2 Semi-structured Interviews

The semi-structured interviews were performed in Thailand and Indonesia and targeted university students (five and eleven participants, respectively). Young adults' travel behavior is more mobile than other age groups and highly volatile and sensitive to the changes in society, economy, and transportation system (Verma et al. 2016). The interviewed schools were Kasetsart University located in Bangkok, Thailand and Muhammadiyah University located in Magelang, Indonesia. The participants mainly between the ages of 20 to 25 were interviewed on July 9th and 12th, 2017, respectively, and the interviews took 2 h each to complete. The interviews were structured with the following question items: (i) students' current transport patterns and their satisfaction with the modes; (ii) students' perceptions about the dis-/advantage of car ownership; (iii) students' car sharing adoption (use) intentions; (iv) potential critical factors affecting their decisions toward car sharing adoption.

Based on the literature review analysis and semi-structured interviews, this study formulated the hypotheses that the identified factors positively (or negatively) influence the car sharing adoption intention.

10.3 Factors Affecting Car Sharing Adoption

The recent studies have observed socio-demographic variables as determining factors that help to increase the diffusion of car sharing services (Kim 2015; Metz 2012; Oakil et al. 2016; Prieto et al. 2017). Some authors examined the influences of attitudinal factors on car travel behavior toward car sharing and car ownership decisions, in addition, while the distance between stations, ability to return the vehicle easily, the service time of day, reservation process, and available type of vehicle were also the factors pointed out by several authors. Overall, a summary of the relevant studies shows that there can be many factors found to influence car sharing adoption decision but grouped mainly into three categories. They are (i) socio-economic and demographic factors, (ii) psychological factors, and (iii) infrastructural factors. Details are described as follows.

10.3.1 Socio-economic and Demographic Factors

Socio-economic factors include variables related to socio-economic development such as population density and urbanization. The socio-economic and demographic factors have been highlighted by many authors to explain the propensity to join a car sharing model (Costain et al. 2012; Prieto et al. 2017; Clewlow 2016; Correia and Viegas 2011; Efthymiou et al. 2013; Zheng et al. 2009). More specifically, they mainly used the market segmentation based on sociodemographic attributes such as age, gender, family size, education, or income level to describe user profiles that are the most likely to use car sharing services.

Several studies found that car sharing choice is driven by young adults between ages 25 and 45 (Prieto et al. 2017; Cervero et al. 2007; Gleave 2017; Le Vine et al. 2014). Because their attitudes toward the automobile are different from those of the older generations, the younger generation is more prone to share cars (Prieto et al. 2017). Travel behavior of young age toward the decreasing preference for owning/using a car for traveling (Noble 2005; Nordbakke and Ruud 2005) suggests that they are more likely to use an alternative transport mode including shared vehicles. The evidence based on user's socio-economic profiles suggested that male respondents tend to favor car sharing services (Burkhardt and Millard-Ball 2006; Prieto et al. 2017; Le Vine et al. 2014; Fukuda et al. 2005). Concerning the result of previous studies with the income and education levels, it seems difficult to make a general conclusion that a certain level is a critical driver for the car sharing adoption. Different income levels may define different motivations to use car sharing services (Burkhardt and Millard-Ball 2006). Several studies show that people with a graduate level of education in the regions of North America and developed cities are more likely to choose a car sharing option (Burkhardt and Millard-Ball 2006; Prieto et al. 2017; Clewlow 2016). However, in developing countries such as India, individuals who are qualified at or above post-graduation levels are likely to buy a car soon (Verma et al. 2016) and little is known toward car sharing.

Household size and family structure are related to the probability of owning cars (Oakil et al. 2016; Ding et al. 2017) and using shared vehicle services (Le Vine et al. 2014) and membership (Coll et al. 2014). Individuals who have experienced car-owning via families show a higher propensity to own a car (Verma et al. 2016) while they are also more likely to be potential users of car sharing (Fukuda et al. 2005; Coll et al. 2014).

The car sharing model tends to work better in metropolitan cities, where higher population density and limited resources such as parking lots lead to more efficient deployment of shared vehicles (Clewlow 2016). Many authors have observed a high population density as an important parameter related to the vehicle owned by residents while insisting that a higher population density is conducive to an increase in car sharing activities as well (Burkhardt and Millard-Ball 2006; Costain et al. 2012).

10.3.2 Psychological Factors

Psychological factors indicate people's perceptions, attitudes, or habits (Ajzen 1991; Fujii and Kitamura 2003). Transportation researchers intuitively assumed that knowing more about travelers' attitudes would help to illustrate how they make transportation behavioral decisions related to trip choice, route choice, and mode choice (Parkany et al. 2004). As a result, psychological factors have been found at least as much influence as demographic factors on the transport mode choice (Parkany et al. 2004; Kuppam et al. 1999).

Recent studies have increasingly emphasized the importance of psychosocial factors in determining car ownership and choice of transport mode (Verma et al. 2016; Anable 2005; Handy 1996; Steg et al. 2001; Verma 2015). For instance, one's motives for value- and convenience-seeking can be a highly influential factor for accepting car sharing (Schaefers 2013). Several studies also showed that the behavioral intent to own a car was driven primarily by the perceived psychosocial values of car ownership (Verma et al. 2016; Verma 2015; Cullinane 2002; Line et al. 2010; Zhu et al. 2012). For example, the car ownership-desire among young adults was much influenced by the psychosocial valuation of cars especially those related to identity, self-image, and societal status (Verma et al. 2016; Cullinane 2002; Zhu et al. 2012).

The environmental motive was not critical, but the altruistic environmental motive could influence consumers' adoption and usage of car sharing (Schaefers 2013). One survey inquiring why they do not own a motorized vehicle also found that there might be a correlation between car sharing membership and environmental attitudes (Clewlow 2016).

10.3.3 Infrastructural Factors

The relevant infrastructural factors impacting the growth of car sharing are related to inter-modality, a distance between a station and home/job and public transport connection. They may include political and financial actors such as parking policies and insurance. Service attributes having administrative characteristics that are manageable by a service provider can be also considered as internal infrastructure-factors; for instance, they are the number of parking lots, vehicle units and types, etc.

A distance to a station from home or job as a critical factor affecting the shared car system adoption has been highlighted by several authors (Costain et al. 2012; Efthymiou et al. 2013; Lindloff et al. 2014). This was seen from the survey results conducted both in Greece, where car sharing was virtually non-existent at that moment (Efthymiou et al. 2013) and in cities like Toronto, where there was a dominant car sharing program (Costain et al. 2012). A long-time span to the parking lot weakens the benefits of car sharing in terms of flexibility and time-saving and thus decreasing sharing activity persistency and usage (Costain et al. 2012; Lindloff et al. 2014).

A previous study investigated the benefits of the cooperation of public transport and car sharing services and shows that users of public transport are potential users for car sharing and vice versa (Huwer 2004). Better public transport connections are positively related to usage intentions (Lindloff et al. 2014), however, the effect of public transport quality on usage intentions or frequency is negative (Verma 2015; Lindloff et al. 2014). The latter indicates the worse public transport, the more the customers are likely to use car sharing.

Some authors (Costain et al. 2012; Habib et al. 2009) suggest that the spatial coverage of sharing services with a great number of parking lots would increase membership and sharing activities. On the other hand, one highlighted the importance of vehicle units over the number of parking lots but noted that vehicles should be accessible within walking distances (Kim 2015).

10.3.4 Conceptual Model Structure Among Potential Factors and Individuals' Car Travel Behavior

To improve our understanding of car travel behavior of prospective car sharing users, an attempt was made to frame a conceptual model that relates individuals' decision to several factors using pictorial representation (see Fig. 10.1).

Individuals' decisions in Fig. 10.1 include car ownership and car sharing adoption decision; car sharing adoption decision indicates an individual's choice when they determine membership registration and usage activity for car sharing services.

Potential factors (variables) structured in three categories, socio-economic and demographic, psychological, and infrastructural factors were considered that were derived from the literature analysis. If there has ever found an attempt to investigate the effect of the factor on decisions to own a car, to be registered as a car sharing member, and to use car sharing services, the model depicted the association using arrows as shown in Fig. 10.1.

For instance, comfort-oriented attitude as a factor is associated with users' perception that car is the most comfortable and safe mode of transport, car traveling is less tiring and improves their personal life. Those who are comfort-valuing are more likely to own a car soon (Verma et al. 2016; Verma 2015). The perceived psychosocial valuation of car ownership as a symbol of modern life, future necessity, and in control of life may be the most influential determinant for future car ownership (Zhu et al. 2012). Financial schemes such as low-interest rates on a car loan can also play a major role in growing car ownership, particularly among the young generation

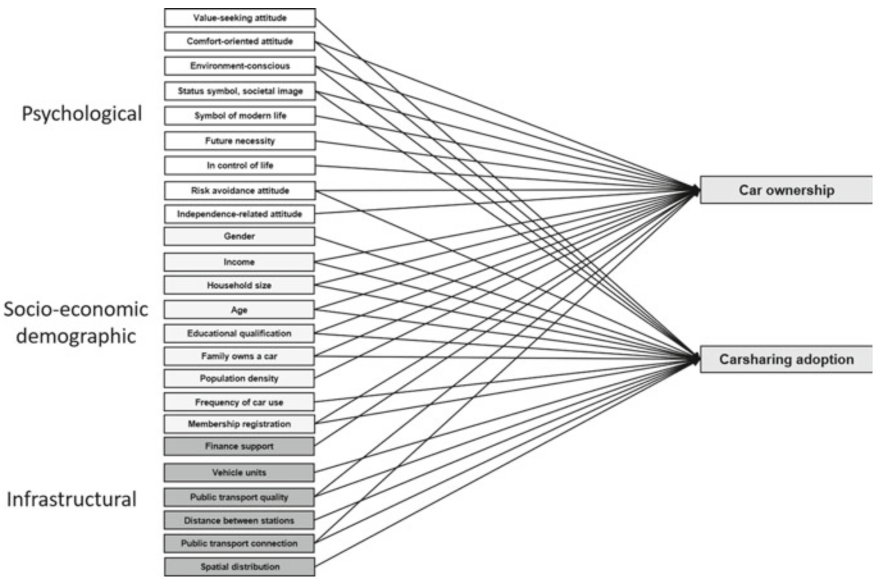

Fig. 10.1 Conceptual model structure between variables and decision related to car travel behavior

in developing economies (Verma 2015). On the other hand, consumers' perception and attitude to avoid the burdens of ownership, the so-called risk avoidance attitude affects the subsequent decision to reduce or give up ownership or to promote car sharing usage (Schaefers et al. 2016).

10.4 Case Study with Semi-structured Interviews

10.4.1 Current Travel Patterns and Their Satisfaction

The analysis of young respondents in Thailand and Indonesia indicates that they both mainly use a motorbike in their daily lives including commuting because of its affordability. In addition, respondents in Thailand sometimes use a rental van service (with a paid driver) for leisure while Indonesian respondents take a bus for visiting parents'/friend's houses. Respondents in Thailand expressed a strong desire to use public transportation for commuting, but their current satisfaction with public transport such as the metro or bus for their trips to school was not so high. This was attributed to the lack of a public transport system or stations with easy access to home and school/work. Young Indonesian respondents appeared to be satisfied with their current transportation, motorbikes during their daily lives. They stated that a motorbike brings them more convenience and comfort when commuting in terms of cost and risk, compared to a private car or public transportation.

10.4.2 Advantages and Disadvantages of Car Ownership

Respondents in Thailand showed a willingness to own and drive a car, especially during the rainy season. Car ownership would work to their advantage in the rainy season. This also suggests that considering climatic attributes as critical factors influencing car sharing adoption decisions should be necessary for the Southeast-Asian region where it has tropical weather and a long rainy season.

Some interesting observations can be made from the comparison between young Indonesian and Thai respondents regarding car ownership. The major difference relates to the perception of risk, where young Indonesian respondents consider this disadvantage of car ownership. They perceived car ownership as an inconvenient mode in terms of maintenance-, repair-, and car accident-risks. Respondents were not likely to buy a car soon in Indonesia even though they can afford to while those in Thailand expressed a strong desire to own a car.

10.4.3 Car Sharing Adoption and Critical Factors

The interview results revealed that young students in Thailand would use a car sharing model for commuting if the one-way service is available. However, most respondents in Indonesia stated that they are willing to use traditional (round-trip) sharing for visiting parents'- or friend's houses during holidays. Convenience was picked as the most important factor for both respondents in Thailand and Indonesia when choosing the mode of transport and deciding to use car sharing as well. While the perception of convenience for Thai respondents was related to accessibility to the mode, time-saving, etc. However, students in Indonesia perceived convenience in terms of being less affected by surrounded traffic congestion, reduced ownership's responsibility (e.g., maintenance, repair, etc.) and the comfort and safe mode as the important factor for car sharing adoption and usage. This suggests that convenience-oriented, and comfort and safe-oriented or risk avoidance attitudes would be an influential factor for car sharing adoption in Thailand, and Indonesia, respectively.

Similarly, as to the question about the perceived importance of the factors, accessibility in terms of short walking distance to stations was the most important in Thailand when considering car sharing option as an alternative mode. For the respondents in Thailand whose intention of using public transportation was very high, the availability and quality of public transport may not affect only car ownership decision, but also car sharing adoption. This result indicates that most Thai respondents consider as critical factors those relevant to infrastructural factors. On the other hand, respondents in Indonesia perceived psychological factors—risk and comfort as critical factors affecting their decisions toward car sharing adoption.

10.5 Hypothesis Formulation

Through the survey using semi-structured interviews, among the relevant variables as shown in Fig. 10.1, this preparatory study identified potential critical factors, formulating the hypotheses that those (variables) can positively or negatively influence individuals' decisions on car sharing adoption in the Southeast-Asia region. Details are given below.

10.5.1 Perceived Benefits of Car Sharing

Car sharing can be profitable for users who use a car for short trips (Lindloff et al. 2014). Compared to expenses of private car ownership, car sharing services give monetary advantage and flexibility to a user while fulfilling the user's mobility needs (Litman 2000). Especially in the Southeast-Asian region like Thailand and Indonesia, the main reason why the respondents chose the current transport mode was also the affordability of motorcycle. Thus, the perceived benefits of using car sharing in terms of cost savings could enhance attitude and influence the intention of car sharing adoption.

H1. Perceived cost saving benefits of car sharing usage is positively related to car sharing adoption intention.

By using car sharing services, users expect the service to help them make their life easier through flexibility, vehicle availability, and variety, time-saving aspect, and simple pricing systems (Schaefers 2013). Lindloff et al. (2014) revealed that convenience was of particular importance as the main drivers of car sharing usage. This is in line with the findings from the semi-structured interviews with the students who point out convenience aspects at the most important criteria when deciding to choose to use car sharing services. Convenience aspects they mentioned especially include comfort, time-saving, reduced ownership burdens, being less affected by surroundings (e.g., rainy season, etc.) compared to motorbikes. Thus,

H2. Perceived convenience aspects of car sharing usage are positively related to car sharing adoption intention.

10.5.2 Infrastructural Variables

Car sharing can be used not only as an alternative for a full commuting mode but also as a feeder transport mode to main public transport. Some cities in Southeast-Asia developing countries like Indonesia do not serve public transportation networks well yet (Belgiawan et al. 2016). Many public transportation users also need to take several modes of transportation to commute their workplaces, thus the latter approach (a feeder mode) may not be odd (Fukuda et al. 2005). Moreover, (traditional) car sharing services do not always provide stations within walking distances. Thus, it can be assumed that intermodal or multimodal mobility behavior is positively related to car sharing adoption intention. Previously, the possibility to easily combine different modes of transport was evaluated positively to car sharing usage frequency (Lindloff et al. 2014).

H3. Inter-modality is positively related to car sharing adoption intention.

10.5.3 Perception of Car Ownership

Car sharing allows drivers to seek alternatives to private car ownership (Shaheen et al. 2009). Risks and responsibilities accompanied by owning a product, are important reasons for users to decide for car sharing use instead of ownership (Schaefers et al. 2016). Many students in Indonesia also have the opinion that people with car suffers from the burdens of ownership, i.e., responsibility for repair, maintenance or replacement, accident management. Hence, we hypothesize that.

H4. Perception of car ownership as burdens and risks is positively related to car sharing adoption intention.

Sociodemographic variables play an important role in determining the diffusion of car sharing services (Prieto et al. 2017). Besides the above-mentioned, therefore, car sharing adoption intention factors need to include understanding the socio-economic and demographic profiles of prospective car sharing users.

10.6 Conclusions and Future Work

This paper provides an understanding of the multiple dimensions of factors influencing the car sharing adoption decision and related aspects of car ownership. They are classified according to the main three groups, socio-economic and demographic, psychological, and infrastructural factors. One of the contributions of this study is, based on the literature review analysis, attempting to try to link the decision on car sharing adoption and car ownership with all those factors defined in this study.

Through the survey using semi-structured interviews, among the relevant variables (factors) defined, this preparatory study identified key factors that might affect the car sharing adoption decision in the Southeast-Asia region like Thailand and Indonesia. Given limitations by the qualitative analyzed results, the extent to which factor is more likely to lead to or deter greater adoption of car sharing cannot be determined. However, this study formulated the hypotheses that those factors influence positively (negatively) individuals' decision on car sharing adoption. These hypotheses can be further tested to investigate the interplay among the factors, and car sharing decisions of Southeast-Asian residents. In addition, future before-and-after studies controlling for each factor in socio-economic and demographic, psychological, and infrastructural groups may help to shed light on how to place effectively car sharing schemes in current transportation environments leads to greater adoption of car sharing and stronger activity persistency.

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Chapter 11
Economy-Wide Material Flow Analysis and Its Projection: DMI Versus TMR in Japan

Shoki Kosai and Eiji Yamasue

Abstract Economy-wide material flow analysis (EW-MFA) is of importance to monitor the material input and to understand the current national material situation. Among various indicators developed for EW-MFA, this study focuses on the direct material input (DMI) and the total material requirement (TMR). DMI is a well-established and simple attribute, which have been widely utilized in the globally well-known institute and national government. On the contrary, TMR is the most encompassing indicator, which involves the evaluation of hidden flows arising from non-economic activities as well as direct and indirect inputs arising from economic activities. Although numerous studies monitored the chronological transition of EW-DMI and EW-TMR, the mechanism and composition depends on each of unique national characteristics. In addition, domestic recycled resources have yet to be fully evaluated in EW-TMR. Furthermore, a top-down approach has been widely employed to obtain the value of TMR for each of categories, whereas calculating the TMR of each product in a bottom-up approach has scarcely been adopted because of its complexity and difficulty. As such, this study calculates the specific TMR of high level of disaggregation of material categories in the bottom-up approach and chronologically analyzes the material input in Japan on both DMI and TMR basis in 1990–2013. Then, considering the relationship between economic development and material utilization, EW-DMI and EW-TMR in 2020 and 2030 are projected by using the historical trend of material input in the course of economic growth. It is found that from 1990 to 2013 in Japan, DMI has constantly decreased by 25.0%, while TMR has increased by 18.4%. The reduction of fine aggregate, gravel, domestic limestone, and stone in the domestic resources primarily contributed to the decrease in DMI, whereas steam coal, iron ore, liquefied natural gas, and coking coal in the imported resources primarily contributed to the increase in TMR. In addition, the overall specific TMR in Japan has continuously increased by 57% from 4.0 Mton-TMR/Mton in 1990 to 6.3 Mton-TMR/Mton in 2013. Then, it is forecasted to constantly increase and, in 2030,

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reach in the range between 11.8 and 14.6 Mton-TMR/Mton. In particular, the recent study revealed that TMR is highly associated with environmental and ecological issues due to mining activities and the specific TMR represents the environmental and ecological impacts arising from mining activities. The forecasted acceleration of overall specific TMR alarmingly raises the environmental and ecological burdens arising from mining activities. The developed algorithm to conduct the material flow analysis by using the bottom-up approach for the calculation of TMR can be readily implemented in any country confronting the issue of sustainable material utilization. It may of use to policymakers in designing more well-grounded material management policy.

Keywords Total material requirements · Direct material input · Material flow analysis · Projection · Mining

11.1 Introduction

In last decades, the global landscape of material utilization has been drastically changed due to the expansion of world population and the rapid growth of industrialization in developing countries. Sustainable material utilization is of fundamental importance to secure economic activities and human wellbeing. Particularly, material inputs in economic activities and material outputs back to earth have a significant pressure on the environment (Bringezu et al. 2003).

Economy-wide material flow analysis (EW-MFA) has been widely utilized for better understanding of the current national material situation (Bringezu et al. 1998). EW-MFA enables the physical material mass flow to be quantified throughout global economy and national material utilization (Kovanda and Weinzettel 2017). The diachronic availability of data collection makes it possible to assess the historical transition of national material flow (Schandl and West 2010).

Various indicators have been developed for EW-MFA (Eurostat 2001). Generally, direct material input (DMI) is a well-established attribute (Patrício et al. 2015). DMI is the sum of domestic extraction used with imports. Meanwhile, the main concern of DMI is a difficulty of setting a proper calculation boundary (Kovanda and Weinzettel 2013). For instance, the total amount of ore is computed in the case of domestic extraction, while only mass of imported semi-finished or finished product is accounted for under the case of metal import (Eurostat 2016). As a result, this discrepancy of recording weight between domestic extraction and import/export leads to a proposal on raw material equivalents (RME) (Muñoz et al. 2009).

Raw material equivalents are defined as *the sum of all raw materials needed for the production* (Kovanda and Weinzettel 2013). DMI is reflected with direct material flow referring the actual mass of product, while RME covers indirect material flow indicating accumulative material requirements to manufacture a product (Schoer et al. 2012). In this paper, both direct and indirect material flows correspond to used materials involved in economic activities.

Meanwhile, RME does not include unused extraction (Moll 2014). Unused materials are the extraction mass which does not enter in economic activities (Eurostat 2007). The unused materials arising from non-economic activities are named hidden flow (HF) in this paper. HF has a significant impact on overall material utilization process and environment (Fischer-Kowalski et al. 2011). In addition, the extraction activities change the landscape, which results in the various critical environmental and ecological issues such as forest fragmentation and biodiversity mitigation (Patz et al. 2004).

As such, taking into account HF arising from non-economic activities as well, total material requirements (TMR) were developed as the most encompassing indicator (Adriaanse et al. 1997). The relations between TMR and environmental and ecological impacts were presented in the earlier study (Kosai and Yamasue 2019). Numerous studies addressed the analysis of EW-TMR in individual countries such as China (Dai and Chen 2010), Uzbekistan (Raupova et al. 2014), Spain (Garmendia et al. 2016), and Finland (Seppala et al. 2005).

Bringezu et al. chronologically evaluated international comparison of DMI and TMR with economic growth and stated that the mechanism and composition of economy-wide TMR depends on each of unique national characteristics (Bringezu et al. 2004). As such, this study focuses on the economy-wide material flow on the basis of DMI and TMR in Japan and observes how the national policy affected the flow. Particularly, most developed countries such as Japan significantly rely on the import of material from overseas (Achzet and Helbig 2013). Due to the increasingly vulnerable balance between demand and supply, appropriate material utilization has been a major concern.

To accurately identify the national economy-wide material utilization pattern, the highly disaggregated classification is used in this study. While the overall material cycle flow study based on DMI has been recently conducted including in recycling materials (e.g. Li et al. 2013), domestic recycled resources have not yet been fully evaluated in EW-TMR. This study includes the recycling flow in the category of both DMI and TMR. In most of earlier studies, the value of TMR for each of category was presented in a top-down manner, whereas this study calculates the TMR of each of product in a bottom-up manner.

The objective of this research is to chronologically analyze and project the material flow from the perspective of both DMI and TMR in the course of economic development.

11.2 Methodology

11.2.1 Classification of Material Categories

This paper basically follows the reported material flow diagram given by Ministry of Environment in Japan (Ministry of Environment 2006). Overall material category is named 1st classification. Subsequently, overall material category is divided into foreign origin and domestic origin. Foreign origin materials are recorded based on imported resources and imported products, while domestic origin materials are comprised of domestic extraction resources and domestic cycled resources. These four components are considered 2nd classification. Subsequently, the second classification is further disaggregated to obtain 3rd classification, comprising of 90 components following the Recycle Data Book published by Japan Environmental Management Association For Industry (2017). Due to the historical data limitation, third classification on a DMI basis in Japan since 1990 until 2013 is recorded here.

11.2.2 Mathematical Relation Between TMR and DMI

The concept of TMR calculation in the bottom-up approach is comprised of two components: the weight of targeted material (kg), which is recorded on the DMI basis, and the weight of all of material inputs including hidden flows to obtain the targeted material (kg), which is recorded on the TMR basis (Adriaanse et al. 1997). Each of two components is referred to the material weight on the DMI basis and the material weight on the TMR basis. The proportion of weight on a DMI basis to weight on the TMR basis depends on the material type, which is named the specific TMR. The specific TMR of material x can be obtained in the following equation.

$$(Weight\ on\ a\ TMR\ basis)_x = (Specific\ TMR)_x \times (Weight\ on\ a\ DMI\ basis)_x \tag{11.1}$$

By obtaining the specific TMR of targeted material, the material weight on the TMR basis is computed based on a data of weight on the DMI basis. Specific TMR of some components in the third classification such as raw materials has been already reported (Nakajima et al. 2006). Meanwhile, the TMR analysis for most of commodities has yet to be conducted. The methodology of estimating specific TMR of commodities is presented as follows.

In the material process, there are two aspects comprising of input and output. Each weight of input materials on the DMI basis is expressed as I_j, while each weight of output materials on the DMI basis is described in the form of M_k. Both j and k are the number of input and output materials respectively. The total weight of input and output materials on the DMI basis given in the form of I and M are computed in the following equation.

$$I = \sum I_j \tag{11.2}$$

$$M = \sum M_k \tag{11.3}$$

Subsequently, S_j is introduced as the specific TMR of each of input materials. Based on the concept of Eq. (11.1), the total weight of input materials on the TMR basis (T) is obtained in the following equation.

$$T = \sum \left(I_j \times S_j\right) \tag{11.4}$$

Since the total weight of input materials on the TMR basis is put on the shoulder of all output materials, it has to be properly allocated to each output material to identify the specific TMR. This study utilizes the monetary value of each output material as an allocation method, since the value of commodity is a major driving force of mining activities (Kosai et al. 2018). P_k is introduced as an unit price of each output material and the allocation rate (r_k) is obtained in the following equation.

$$r_k = \frac{M_k \times P_k}{\sum (M_k \times P_k)} \tag{11.5}$$

The weight of each output material on the TMR basis (T_k) is obtained in the following equation.

$$T_k = (T - M) \times r_k + M_k \tag{11.6}$$

The specific TMR of each output material (S_k) is computed in the following equation.

$$S_k = \frac{T_k}{M_k} \tag{11.7}$$

A set of process for obtaining specific TMR is applied to the 3rd classification. After obtaining the weight on the DMI basis and the estimated specific TMR in each of 3rd classifications, the weight on the TMR basis is obtained by using Eq. (11.1). Subsequently, 1st and 2nd classification on both DMI and TMR basis is computed in the form of DMI_c and TMR_c respectively.

$$DMI_c = \sum_{x}^{c} M_x \tag{11.8}$$

$$TMR_c = \sum_{x}^{c} M_x S_x \quad (11.9)$$

where, c = 1: 1st classification, 2: 2nd classification.

Finally, the overall specific TMR under the 1st classification is obtained in the following equation.

$$Overall\ specific\ TMR_{c=1} = \frac{TMR_{c=1}}{DMI_{c=1}} \quad (11.10)$$

Referring the work (Yamatomi 2008), the chronological change of ore grades is assumed in this analysis.

11.2.3 Projection Analysis

Chronological material flow reflects the transit of economic growth, since GDP per capita is a major driver for material input. Given that the reported correlation distinguishes specific country trade, the material input with the economic development in Japan is analyzed in this paper. The data of GDP (the current US dollar) and population in Japan in 1990–2013 is taken from The World Bank (The World Bank 2015), and DMI per capita as well as TMR per capita are computed. Then, as seen in the work by Bringezu et al. (2003), the regression equation representing the relationship between the material input indicator and the economic development indicator is obtained by using various models. Following the by Bringezu et al. (2003), the relationship between DMI per capita and GDP per capita is analyzed by using quadratic model, while the relationship between TMR per capita and GDP per capita is analyzed by using linear, quadratic, and cubic models. This regression equation is used to indicate the potential rage of TMR in the projection analysis. The historical trend of material input in the course of economic development will be extended for the determination of EW-DMI and EW-TMR in 2020 and 2030. The forecasted population and GDP in Japan are taken from the Institute of Energy Economics, Japan (2015). It must be noted that this projection analysis will be conducted based on the assumption that the economic structure will follow the historical trend.

11.3 Results and Discussion

11.3.1 DMI and TMR in Japan in 1990–2013

The weight on both DMI and TMR basis under 1st classification in Japan in 1990–2013 is presented in Fig. 11.1. Material input on the DMI basis in Japan has constantly

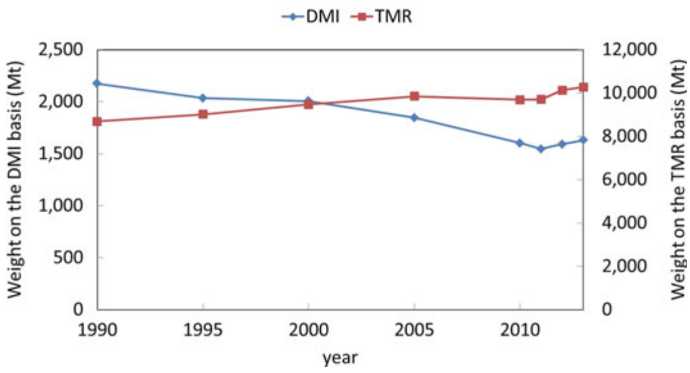

Fig. 11.1 DMI and TMR under 1st classification in Japan 1990–2013

decreased by 25.0% from 2170 million ton in 1990 to 1630 million ton in 2013. On the contrary, material input on the TMR basis in Japan has successively increased by 18.4% from 8680 million ton in 1990 to 10,300 million ton in 2013. The opposite trend in the chronological transition of material input between DMI and TMR under the 1st classification is examined in Japan.

The weight on both DMI and TMR basis under 2nd classification in Japan in 1990–2013 is presented in Fig. 11.2.

The trend of DMI is first examined as follows. From 1990 to 2013, domestic resources decreased by 54.4%, while imported resources, imported products and domestic cycle resources have increased by 16.5%, 74.2%, 13.5%, respectively. Despite of the significant increase in imported products, its change does not explicitly affect the result of 1st classification because of its small amount. Since the domestic

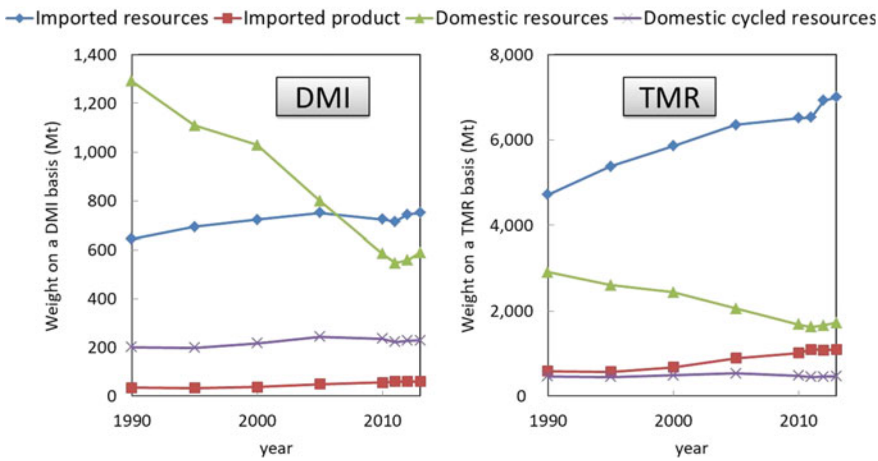

Fig. 11.2 DMI and TMR under 2nd classification in Japan 1990–2013

resources have covered the great share of the total DMI, its continuous decrease greatly contributed to the reduction of total DMI under 1st classification.

The increase of utilization of domestic cycle resources would imply a positive effect of national recycling policy. Japanese government enforced the Basic Act for Establishing a Sound Material-Cycle Society in 2000, which aims to mitigate the waste amount, to consider its usefulness and to establish the material cycle systems from the perspectives of reduce, reuse, and recycle (material and thermal) (Ministry of Environment 2000). Under this principle, Act on the Promotion of Effective Utilization of Resources was enforced in 2001, which obligates companies to rationalize raw material utilization to mitigate the generation of by-products, to use recyclable materials, and to promote the utilization of by-products (Ministry of Economy 2015). It must be noted that domestic cycled resources reached its peak in 2005, whereas after that it has slightly decreased, which would indicate that, in spite of the positive effect of earlier national recycling policy, long-termed policy is required.

The trend of TMR is then examined as follows. Due to the increase in the volume of imported resources, it has increased by 48.5% from 4710 million ton in 1990 to 7000 million ton in 2013. Since the imported resources cover the great share of total TMR, the significant increase in the imported resources mitigated the the influence of increase in the domestic resources and contributed to the overall increase of total TMR under 1st classification.

The weight on both DMI and TMR basis under 3rd classification in Japan 1990–2013 is obtained. The top 7 categories under 3rd classification as a major influential factor are presented in Fig. 11.3.

The trend of DMI is first examined as follows. Fine aggregate, gravel, domestic limestone, and stone have decreased significantly by 58.6%, 52.6%, 83.9%, and 25.3% from 1990 to 2013, respectively. These are categorized in the domestic resources under the 2nd classification, which primarily contributed to the decrease in

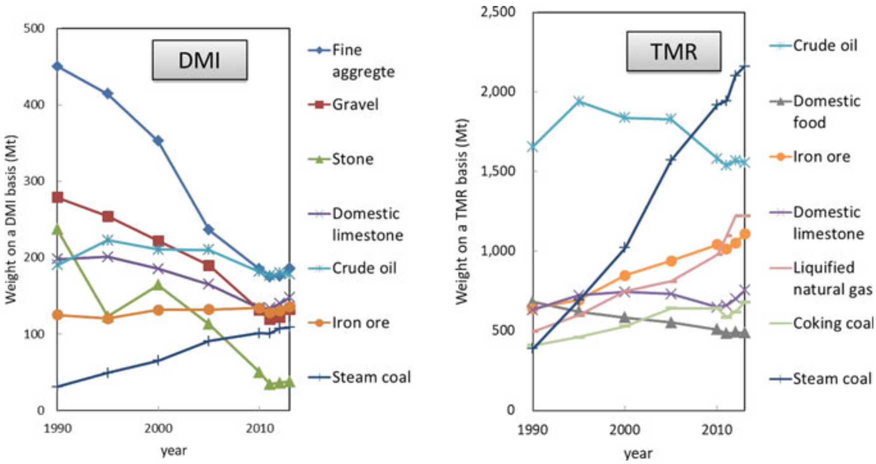

Fig. 11.3 DMI and TMR under 3rd classification in Japan 1990–2013

domestic resources. This decrease is highly associated with the national policy. Public investment into infrastructure construction had previously been a major driver for the economic growth to address a business depression in Japan. However, Japanese government reconsidered the national financial management and stringently adopted the only inevitable investment. As a result, the public investment into infrastructure construction has been mitigated by 10.7% in 2002, 3.9% in 2003, 3.5% in 2004 compared with the preceding year. The vital cut of public investment into infrastructure construction would lead to the mitigation of aggregate, gravel, and stone.

The trend of TMR is then examined as follows. The fine aggregate, gravel and stone aforementioned in the top DMI are not presented due to their small specific TMR. Instead, steam coal, iron ore, liquefied natural gas, and coking coal have significantly increased by 458%, 73.4%, 147%, and 66.1% respectively from 1990 to 2013. These are categorized in imported resources under the 2nd classification, which primarily contributed to the increase in imported resources. Particularly, the ore grade has recently declined and it is unlikely to find new high grade deposits (Watling 2015). After over-exploitation of richer ore grades, mining activities globally move to lower grade ores. In addition, the stripping ratio associated with mine depth has decreased as well over time (Xian et al. 2016). The deterioration of resource landscape requires larger amounts of unused materials (Crowson 2012). The rise of exploiting unused materials has contributed to the increase in imported resources on the TMR basis.

11.3.2 Sensitivity Analysis

Although this study assumes the transition of ore grade based on the work (Yamatomi 2008), the accuracy of assuming degree of decline in ore grade is a major concern. To evaluate the influence of ore grade, this study compares the overall TMR under the case of between the assumption of the ore grade transition and the non-consideration of the ore grade change. The growth rate of TMR and overall specific TMR under 1st classification in Japan from 1990 to 2013 is presented in Table 11.1.

Given the potential decline in ore grade, it is obvious that the greater growth rate of TMR-related values with the consideration of ore grade change is indicated. Notably, even if not considering the ore grade change, the TMR-related values constantly increase from 1990 to 2013. While most of earlier studies have not clearly mentioned

Table 11.1 Growth rate of TMR-related values under 1st classification in Japan from 1990 to 2013

Content	Consideration of ore grade change (%)	Non-consideration of ore grade change (%)
TMR	+18	+7
Overall specific TMR	+57	+42

the situation of ore grade, this present study quantitatively presented the influence of ore grade transition on the overall TMR calculation. Although this study assumes that the ore grade is linearly declined, an application of other models such as an exponential model would result in the greater increase in TMR-related values.

11.3.3 Projection Analysis

Projection of both EW-DMI and EW-TMR under the 1st classification is presented in Fig. 11.4.

It is projected that DMI will significantly decrease by 40.3% in 2020 and 58.3% in 2030 compared to 1990, respectively. In addition to the historical trend of decreasing DMI per capita in the course of economic development, the population in Japan is expected to constantly decrease in coming years, which will lead to the great reduction of material input on the DMI basis (The Institute of Energy economics 2015). Meanwhile, compared to 1990, TMR in 2020 will increase by 24.4–27.0% and in 2030 by 22.9–45.9% compared to 1990, respectively. Under the proposed models other than the linear model, the material input on a TMR basis is projected to increase from 2020 to 2030 in spite of population decrease.

The potential range of weights on the TMR basis under the 2nd classification in 2020 and 2030 are presented in Fig. 11.5. It is projected that both imported resources and imported products increase from 2013 to 2030 and the domestic resources decrease, irrespective of the potential range. The potential domestic cycled resources in 2030 are forecasted to remain the same as 2013 or significantly decrease from 2013.

In particular, the steam coal, hard coal, liquefied natural gas and copper ore in the imported resources and for electrical appliances in the imported products is projected to exponentially increase with high correlation. The demand side management for these categories has to be carefully taken into account.

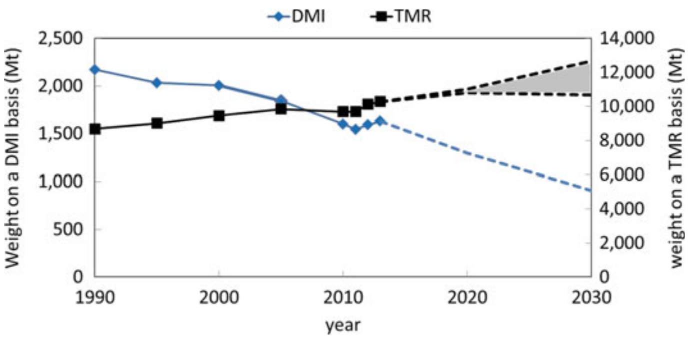

Fig. 11.4 Projection of both EW-DMI and EW-TMR under the 1st classification

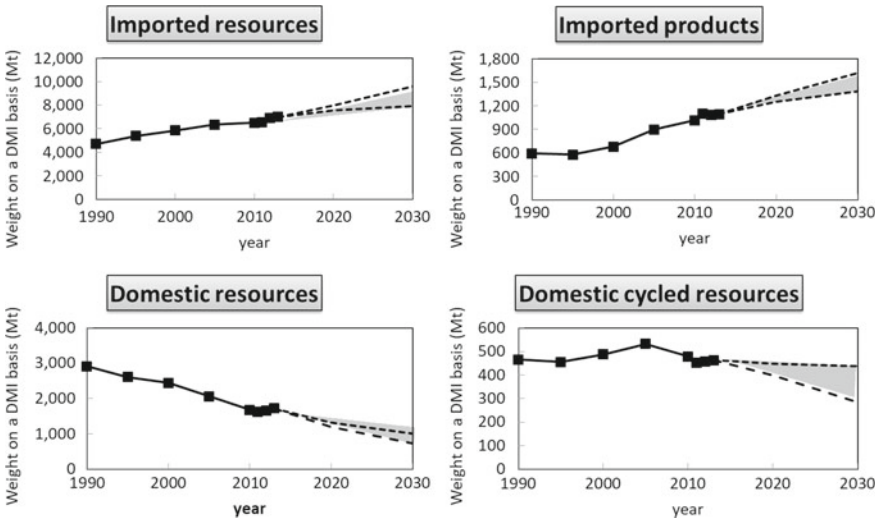

Fig. 11.5 Projection of TMR under the 2nd classification

Coal and liquefied natural gas are primarily used for electricity generation. In the aftermath of Fukushima Daiichi nuclear power plant accident in 2011, all nuclear power plants in Japan has shut down, which had previously contributed approximately 30% of the electricity supply (Kosai and Unesaki 2018). To compensate the sudden loss of electricity supply from nuclear power, the import of coal and liquefied natural gas has increased. From the perspective of not only carbon emissions but also TMR, the Japanese government needs to consider the exploration of new mine with financial and technical support and the replacement of some amounts of coal and liquefied natural gas with other sources with less impact of mining activities.

In addition, the mining situation of copper and other ores is highly expected to be deteriorated in future, which causes the increase of specific TMR. The metal mining and utilization is highly associated with the issue of raw material criticality. In addition to the demand of metal use on the DMI basis (e.g. Helbig et al. 2016) and environmental burdens (e.g. Nassar et al. 2012) widely accepted as an indicator of metal criticality, the exponential increase of metal mining on the TMR basis would raise more alarmingly the criticality of metals in future. In order to avoid this issue, the wise use of recycled metals is required. However, among the domestic cycled materials, both recycled domestic iron scrap and recycled domestic non-ferrous metallic scrap on a TMR basis are projected to decrease. Although the amount of recycled metal exports has continuously increased in a last decade [41], its use as domestic cycled resources would contribute to the mitigation of metallic input on a TMR basis.

Then, material productivity on both DMI and TMR basis in 2020 and 2030 are projected. The result is presented in Fig. 11.6. In the case of both DMI and TMR, material productivity in 2020 and 2030 is forecasted to increase from 2013, whereas

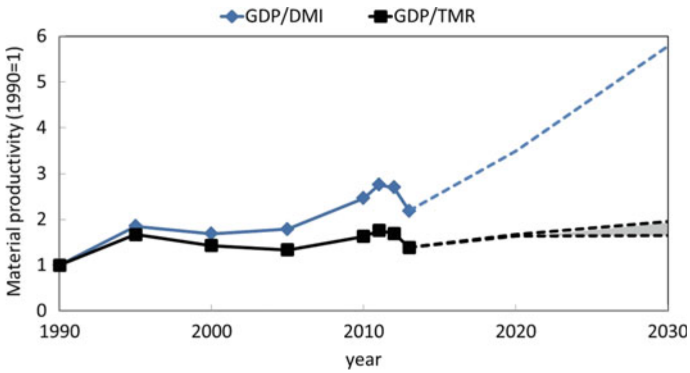

Fig. 11.6 Projection of material productivty

the significant gap of growth rate can be observed. Material productivity on the DMI basis is projected to constantly increase by 578% in 2030 compared to 1990. Meanwhile, that on the TMR basis is forecasted to reach in the range between 158 and 196%, and there is a possibility that the material productivity on the TMR basis remains the same between 2020 and 2030. The material productivity in Japan has been monitored only on the DMI basis so far, which potentially risks reaching a short-sighted conclusion of relationship between economic development and material input in the policy making process.

Finally, the overall specific TMR in Japan in 1990–2013 and its projection in 2020 and 2030 is presented in Fig. 11.7.

The overall specific TMR has continuously increased by 57% from 4.0 Mton-TMR/Mton in 1990 to 6.3 Mton-TMR/Mton in 2013. Then, it is forecasted to

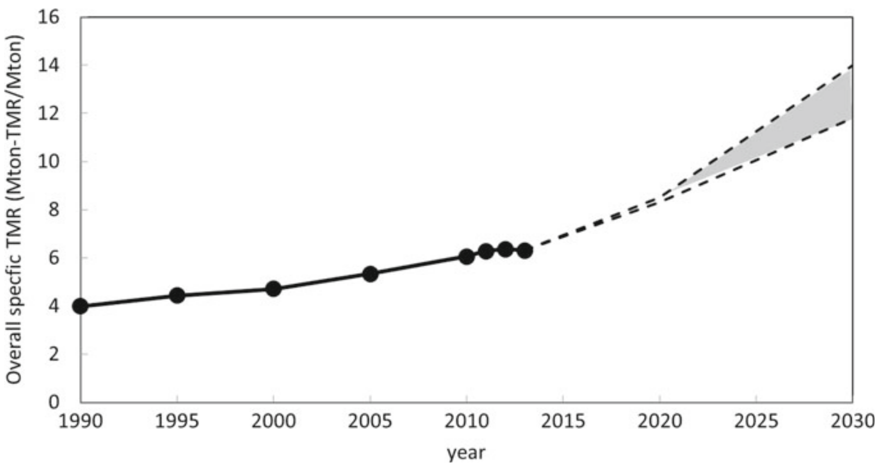

Fig. 11.7 Projection of overall specific TMR

constantly increase and, in 2030, reach in the range between 11.8 and 14.6 Mton-TMR/Mton. It must be noted that the average of annual increasing rate is 10.0% in the last 23 years from 1990 to 2013, while it is expected to be 32.3–45.2% in the projected time scale from 2013 to 2030.

EW-MFA is often used for the environmental analysis (e.g. embodied emissions). the concept of TMR is highly associated with environmental and ecological issues due to mining activities and the specific TMR represents the environmental and ecological impacts arising from mining activities (Kosai and Yamasue 2019). The continuous increase in the overall specific TMR shows that the material use in Japan in last two decades has caused increasingly environmental and ecological impacts in the global mining origins. In fact, global warming potential (GWP) and TMR have a different trend (Kosai and Yamasue 2019). Differing from carbon emissions, this study highlighted the environmental and ecological issues arising from mining activities, considering the potential acceleration of overall specific TMR.

11.4 Conclusion

This study has computed the specific TMR of high level of disaggregation of material categories in the bottom-up approach and chronologically analyzed the material input in Japan on both DMI and TMR basis in 1990–2013. Then, considering the relationship between economic development and material utilization, EW-DMI and EW-TMR in 2020 and 2030 have been projected by using the historical trend of material input in the course of economic growth. Findings are as follows:

- From 1990 to 2013 in Japan, DMI has constantly decreased by 25%, while TMR has increased by 18%.
- The reduction of fine aggregate, gravel, domestic limestone, and stone in the domestic resources primarily contributed to the decrease in DMI.
- Steam coal, iron ore, liquefied natural gas, and coking coal in the imported resources primarily contributed to the increase in TMR.
- It is projected that, compared to 1990, DMI will decrease by approximately 40% in 2020 and 58% in 2030 while TMR will increase by 24–27% in 2020 and by 23–46% in 2030.
- The overall specific TMR has continuously increased by 57% from 4.0 Mton-TMR/Mton in 1990 to 6.3 Mton-TMR/Mton in 2013. Then, it is forecasted to constantly increase and, in 2030, reach approximately in the range between 12 and 15 Mton-TMR/Mton.
- The forecasted acceleration of overall specific TMR alarmingly raises the environmental and ecological burdens arising from mining activities.

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Chapter 12
Ecological Smart and Sustainable Waste Management: A Conceptual Framework

Yun Arifatul Fatimah, Rochiyati Murniningsih, and Agus Setiawan

Abstract This study has an objective to formulate a conceptual framework of sustainable municipal waste management in Indonesia. The framework validation was taken place in four urban cities in Indonesian, inorder to identify whether the framework applicability to be used in developing country environment. The approachs to the study consists of literature review and formulating conceptual framework, validating and revising the conceptual framework based on phenomenon and local tradition, and implications of the revised framework. Based on the analysis, it was found that there are two specific components that called animal edible materials and combined waste bank which should be integrated into the revised framework. Internet of Thing makes the integration possible. The revised framework undertakes to resolve complex and huge amount of waste, to maximize economic benefit from the waste, to increase effective waste management, to provide affordable green material food for animals, and to substitute expensive animal concentrate, and to provide better public health sectors.

Keywords Ecological · Smart · Sustainable · Waste management · IoT · Framework

12.1 Introduction

In the current fourth industrial revolution, the role of Information Communication Technology (ICT) including Internet of Things (IoT) in manufacturing and service processes are getting prominence and essential due to the demand for high speed, reliable, accessible and quality services and products. IoT offers smart coordination and sustainable environment that are the foundation of current industry 4.0 (Khaitan and McCalley 2015).

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IoT is also a promising solution to solve the environmental problem, including waste management, which has been a fast-growing issue of developed and developing countries (Esmaeilian et al. 2018; United Nations 2010). Reviews on some research papers found some waste management models and practices that discuss the potential advantages of IoT to achieve smart and sustainable waste management (Anagnostopoulos 2017; Aleyadeh and Taha 2018; Chen et al. 2018; Adam et al. 2018).

However, the use of IoT in waste management practices was found very limited in developing countries such as Indonesia. Thus, a recent study has designed a new fundamental framework of smart circular waste management (SCWM) which uses IoT as the center of the waste management system. The framework was developed based on literature reviews and case studies conducted in four cities such as Jakarta, Semarang, Yogyakarta, Magelang. It focuses on the potential use of ICT and IoT in waste management through a number of phase including usage (i.e. consumption), collection, sorting, transportation, treatment (i.e. technical, biological and energy recovery) and disposal.

This paper is organized into six sections, including introduction, research method, results of literature review and formulating conceptual framework, validating and revising the conceptual framework based on phenomenon and local tradition, implications on the revised framework and conclusion.

12.2 Research Method

Four steps research method including reviewing some literature from recent publications, formulating conceptual framework, validating the conceptual framework by identifying local tradition and phenomenon through direct observation and communication with stakeholders (i.e. government staffs, community, industry and experts) are used in this research. The results analysis requires some adjustment and improvement for appropriate waste management system that locally adaptable, and the implication of the revised framework.

12.3 Results of Literature Review and Formulating the Conceptual Framework

Most of the existing framework include four essential sustainability aspects including economic, social, environment and governance as the key players of sustainability pillars. What is lacking is how the relationship among the four aspects, remains unclear. In this study, we rearrange the four pillar as seen in Fig. 12.1. Since the governance dominated by government, waste management is strongly directed by the government. Government has significant roles in determining the regulation,

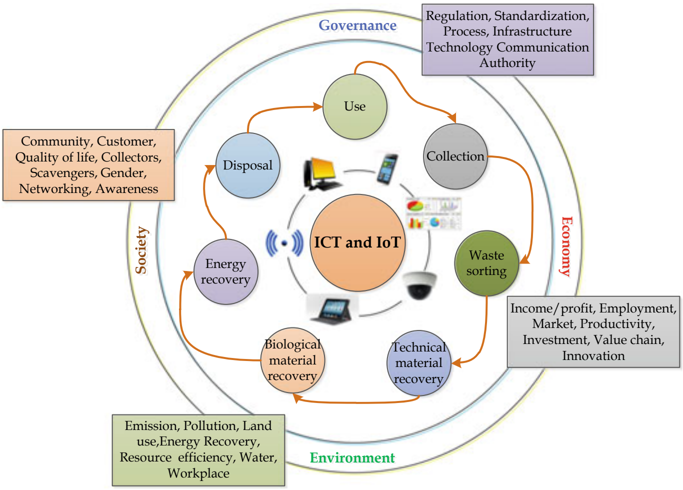

Fig. 12.1 Smart Circular waste management framework

standardisation, infrastructure, technology, community and authority. Hence, the governance pillar places on the outmost layer along with other three pillars on the conceptual framework in Fig. 12.1. The next pillar is economic, social and environmental aspects. Economy aspects concern on income, employment, market, productivity, investment, value chain and innovation. Environmental aspect focuses on emission, pollution, land use, resource efficiency. Social aspects are community participation, customer involvement, quality of life, collectors and scavengers contributions, gender equity, networking opportunity and awarness. The IOT is the key facilitator of the interconnction and integration of information, infrastucture, service and communication of the aspects to achieve sustainability effectively and efficiently.

Eventhough the four pillars already in place, the previous existing waste management data, mostly outdated, unintegrated, and inaccurate. The implementation of ICT and IoT in the system, provides a comprehensive, up to date, accurate, and real time information of a circular waste management: include the use of product, collection, waste sorting, technical material recovery, biological material recovery, energy recovery and landfill. The IoT and ICT ensure that all input process and output of the SCWM can be monitored, evaluated, integrated and accessed anywhere and anytime by the stakeholders and help them to make decision.

A further analysis was conducted to validate the conceptual framework in Fig. 12.1 and to determine the appropriate and suitable adjustments to make sure that the proposed system is economically, socially and environmentally feasible for local Indonesian urban cities.

12.4 Validating and Revising the Conceptual Framework Based on Local Phenomenon and Tradition

In the validating analysis, it was found that there is a specific waste characteristic for a variety of animal edible materials and a combined waste bank that has not been discussed in the proposed conceptual framework.

12.4.1 Validating Framework Based on Local Phenomenon and Tradition

Waste characterization is an essential part of waste collection and sorting in a region. Waste is usually characterized into some fractions including organic (e.g. food from the household, vegetables, and fruits from markets) and non-organic waste (e.g. plastic, paper, metals, glass) (Aprilia et al. 2013; Tchobanoglous et al. 1993). Different natural factors (e.g. geographical area, climate) and human life factors (e.g. household income, culture) in certain region produce different waste characteristic (Han et al. 2015, 2018). There are some effective waste treatments promoted to create values from the waste. Composting, fermentation, bioreactor landfill, semi-aerobic landfill, and waste to energy are common effective treatment technologies for organic waste, while recycling, repair, reconditioning, remanufacturing are an effective treatment for non-organic waste (Han et al. 2015; King et al. 2006; Tisserant et al. 2017; Jereme et al. 2014). The selection of an appropriate treatment technology is depending on the characteristic of the waste.

Smart and sustainable urban and semi-urban waste management system does not mean blindly using ICT, forgetting local wisdom, and avoiding the indigenous phenomenon. In this research, smart and sustainable waste management is defined as a waste management system which able to manage resources and waste efficiently by respecting local wisdom and phenomenon and by optimizing the use of ICT and IoT.

Therefore, some old tradition and local circumstance are considered in order to optimize waste management. An old tradition of Ancient India for maintaining the environment through a rectangular waste recycle method represents an old practice of sustainable waste management (ScienceIndia 2017). Aztec waste management is the other old tradition which shows how the ancient people already aware of the resource conservation through a zero-waste society (United Nations University 2014). Waste community (i.e. waste pickers or scavenger) in some countries such as Nepal, Nigeria, China, and India has become important component of the sustainable waste management system. It is approved that their participation in the waste collection system significantly reduces the amount of waste in the countries (Han et al. 2018; Oguntoyinbo 2012; Li et al. 2012).

In Indonesia, the involvement of society (i.e. scavengers and waste bank community) in national waste management is clearly stated in President Regulation no 97—2017 and Environment Ministry Regulation no 10—2018. Even though scavenger is categorized as an informal sector in the waste management system, the existence of scavengers reaches 5 million in Indonesia, which is expected to reduce 30% of national waste at source (Greeners 2018). In addition, the existence of waste bank in Indonesia which is about 5244 units was expected to reduce 1.7% of national waste and it was valued as 1.48 billion IDR in 2017 (Greeners 2018). The empowerment of these communities could become social investment not only to reduce waste, but also to develop human productivity, cooperation, and efficiency.

Some valuable lessons from the local phenomenon and old tradition are as follows.

Waste is a valuable resource—Waste through reusing, recovering and recycling processes are good resource and valuable materials (Cairns et al. 2018; Joseph et al. 2016). The old tradition discovered that waste including organic materials is very valuable, so the waste was recycled for farming and agriculture materials. Under this consideration, current waste management should consider waste recycling and resource efficiency to transform waste into resource toward sustainable waste management.

Waste community is a powerful tool—The local tradition shows that waste community such as scavengers is crucial in developing countries waste management (Dhewanto et al. 2018; Aprilia et al. 2011). The existence of scavengers or waste pickers who like to collect non-organic waste (i.e. electronic, papers, plastics, metals, glass) has created a competitive economy that helps to reduce the waste and clean the environment. However, many of us often look scavenger as dirty part of environment system. The number of scavengers is uncounted as they come and go unregistered, and unrecognized and often rejected in the system. However, if the cities want to optimize the waste recycling process, the government should work together with the informal sectors and community.

Waste bank is a green entrepreneur—Waste bank as a community-based enterprise in developing countries has developed a waste collection culture that reduced waste and used the waste as economic sources to meet their family need (Dhewanto et al. 2018). The waste bank provides "waste-money conversion system" in which customer (i.e. community) can make a deposit with their waste and earned a monetary value from their waste. This phenomenon demonstrated the power of community to provide a green entrepreneurial motivation and a cleanliness lesson in the society. Supports from the government through policy, subsidies, and assistance to the enterprise are urgently required.

The following four case studies were used to explore local phenomenon and tradition to validate the conceptual framework.

BantarGebang—BantarGebang is Jakarta waste final disposal center. Bantargebang receives about 7400 ton/day of mixed waste. The waste characteristic mainly consists of organic waste (i.e. vegetables, fruits) came from the markets and household. The organic waste contributes 55% of total waste. Waste treatments in this disposal center are composting, recycling, water waste installation, cover landfill, and electricity generation from waste. There are about 7000 scavengers categorized as non-formal sector work in this area, while there are about 1.500 waste bank in Greater Jakarta They help to collect some valuable material (i.e. plastic, paper, metals) which are then sent to recycling industry or other 3rd party treatment industries.

Jatibarang—Jatibarang is Semarang waste disposal centre. Jatibarang receives about 800 ton/day which has treatments of composting, recycling electricity generation, landfill and animal feeding materials. The main waste characteristic is organic waste which accounts about 61.5% of total waste. Globally, there are about 150 scavengers work in the waste disposal centre, and about 220 waste banks are handled non-organic waste in Semarang.

Piyungan—Piyungan is Yogyakarta waste disposal centre. Piyungan receives about 600 ton/day, which are managed through recycling, animal feeding materials, and landfill. The waste characteristic is dominated by organic waste which is about 57% of the total waste. There are about 450 scavengers work in the regions and about 470 waste banks working for non-organic waste management.

Bayuurip—Banyuurip is Magelang waste disposal centre. Bayuurip receives about 250 ton/day which are treated into biogas, compost and landfill processes. The waste collected in the disposal centre is mainly organic waste, which accounts for 75.5% of total waste. There are 585 waste banks in Magelang region and about 38 main waste banks covering 80 unit waste banks in Magelang city.

The current situation of waste managemen in the four cities found similar tradition, wisdom and phenomenon which lead to some results. Firstly, organic waste is the main characteristic of waste in the cities. The organic waste is contributed from market and household waste which are potensial to be transformed into animal edible materials. Secondly, combined waste community including scavengers and waste banks play important role to benefit the economic, social and environment development in society. Thus the combined waste community is essensially integrated into the waste management system.

12.4.2 Revising the Conceptual Framework

From the validating analysis, it is found two new components, such as animal adible material and combined waste banks. Due to the important of the two components, they have to be included into the framework. Hence, the revised framework was developed into three set of waste management including SET1—smart circular waste management, SET2—animal edible material, and SET 3—combined waste banks, as presented in Fig. 12.2. Each of SET is explained as follows.

SET 1—Smart circular waste management—Circular economy (CE) is defined as an approach to optimize the value and to reduce the waste by improving the ways

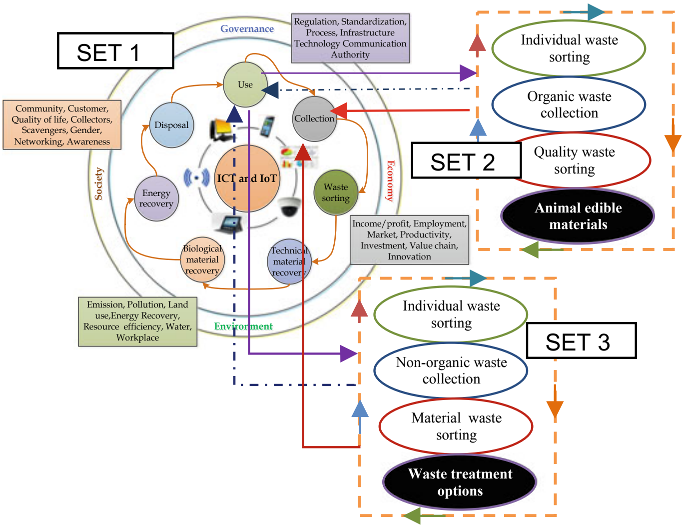

Fig. 12.2 Revised framework of SCWM

how a product or a service is designed, produced and used, and it covers material to business approach (Cairns et al. 2018).

The smart circular waste management goes beyond the circular economy, in which the value of the waste is explored at an early stage of the collection process, the quality of waste is sorted and the generation of residual waste is minimized. The animal edible material component and combined waste banks which are introduced to the revised system is designed to transform waste into valuable resources at the beginning of the system, and to reduce the residual waste sent to landfill. The system applies ICT and IoT (e.g. sensors, and smart technologies) to integrate all activities regarding waste management system and to maintain the reliability, validity, availability of waste informations.

The waste flow stream under the revised framework consists waste generation (i.e. waste source), waste collection, sorting, transportation, processing (i.e. treatment) and disposal (i.e. landfill), as presented in Fig. 12.3.

Waste which consist of organic and non-organic wastes are usually categorized as non-valuable materials. They are mostly generated from municipal, households, markets, shops, and streets. It is expected in the revised framework that the waste has been separated from the source, and divided into three categories, which are organic, non-organic and invaluable waste. There will be bins (i.e. green, yellow and red) provided for the community. Organic waste is handled by specific trucks utilized by GPS technology, and has a function to monitor the route and trips of the vehicle before they manufacture. Sorting activity is facilitated with sensors technology to identify waste materials. The sensor will identify Non-organic waste (i.e. plastic, papers, rubbers, steels, woods, electronics, batteries) is collected and packed by scavengers for recycling/reuse/remanufacturing process, while organic wastes (i.e. food, leafs,

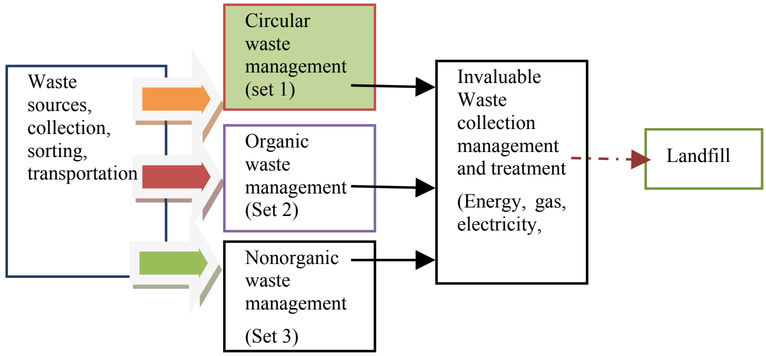

Fig. 12.3 Waste flow of revised SCWM

grass) are separated and sent to the organic waste collection center for further special treatment.

Quality organic waste is transferred from the on-site points to temporary collection center, and then from collection center to animal edible material production areas using the truck vehicles (i.e. small, medium and big vehicles). Each vehicle is set with GPS for monitoring the route and schedule. Non-organic waste collected in waste banks is treated separately based on its characteristic and materials. A number of treatment technologies such as recycling, remanufacturing, refurbishing, and energy conversion are expected to be introduced by third-party industries. A small of waste residue or even zero waste is expected to be produced in the whole waste management cycle and is safely disposed to landfill.

The circular economy practices are adopted during the smart waste management cycle. The framework integrated all products and process used in the edible waste management system and the waste banks system through ICT and IoT infrastructure, to improve governance, social, economic and environmental functions.

The circular waste management (SET1) represents critical activity in the framework. The waste flow shows a set of circular activity consisting of use, collection, waste sorting, technical material recovery, biological waste management, energy recovery and disposal. ICT and IoT applied in the waste management system are subjected to integrate and interconnect all the activities chain to reduce the cost, to achieve resource efficiency, to reach environmental impacts and to improve human social quality.

SET 2—Animal edible material component—For the revised framework, scavengers are expected to be one essential player in waste collection process. In the waste collection cycle, organic waste is separated by the help of scavengers who collect all non-organic waste in the temporary waste collection center. The scavenger is expected to be empowered by the local government as contracted employees. Their responsibility is to collect the non-organic waste, and segregate the waste from organic waste. The organic waste is then sent to waste production center by municipality trucks to be further selected into good and bad wastes. Some sensors are used to identify the biological quality of the waste to do the selection process. The quality organic waste is processed into animal-edible materials as illustrated in Fig. 12.2.

The process refers to biological process under specific circumstance by the help of anaerobic fermentation technology, to produce hygiene and quality materials. The process for producing animal edible materials are identifying the quality material indicators of the organic waste, determining the appropriate fermentation technology for the organic waste, determining the production method of the edible waste materials, implementing the production of the edible waste materials through a case study, and analyzing the technical, economic, social and environmental benefits.

Specific characteristic of quality organic waste used in the process are voluminous, high water concentration, high nutrition (even better than grass), and less contained chemical material. Therefore, an-aerobic fermented technology is considered to be suitable for the organic waste characteristic found in the four cities. The technology is simple and economically beneficial for high water density material, as the technology does not require drying process thus more efficient in time, cost and labor hour. The technology is also environmentally friendly process, as it does not produce any smells and pathogen bacteria. Long life time is the other consideration why this technology is chosen. In additional, the technology is safe for human consumption as it does not contain any pathogen microorganism. The process for producing the animal edible products are illustrated in following Fig. 12.4.

Process applied in the case study offers quality and economic values of the animal edible product such as PH 3.82–4.28, NH_3 concentrate of 7.12–22.0 mM, VFA concentrate of 34.02–80.78 nM, dried material digestibility in vitro of 48.43–61.68%, organic material digestibility in vitro of 48.28–60.11%, improvement of animal weight, improvement quality milk production. In addition, the material is not

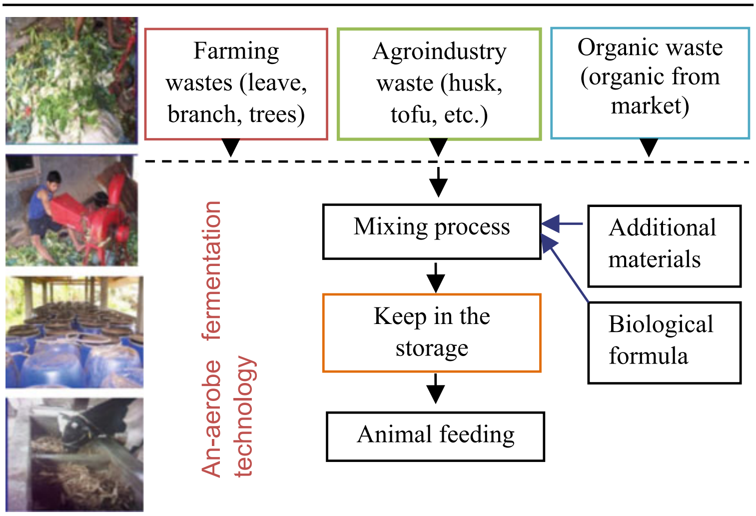

Fig. 12.4 Process of animal edible product

smelly, life longer, probiotic content, easy to make and economically viable, safe to be consumed by animal and at competitive price.

The animal edible material solves complex and hug amount of waste, to maximize economic benefit gathered from organic waste, to increase effective organic waste management, to provide affordable green material food for animals, and to substitute expensive animal concentrate.

SET 3—Combined waste bank—Waste bank is a community based waste management with a specific purpose to manage waste through collection, sorting, and depositing valuable waste, and to convert the waste into certain value of money, products (e.g. rice, sugars, vegetables oil) or facilities (e.g. electricity bill, water, cellular credit). The waste bank development also offers benefits to the society including the raising of community awareness on waste collection, the increase of community income, the improvement of standard life, and the reduction of waste sent to landfill. There are two type of waste bank (i.e. conventional and online waste bank) developing in Indonesian community.

The conventional waste bank has similar system of commercial bank, in which the community (i.e. waste bank customers) brings their valuable waste (i.e. paper, glass, bottle, plastics, steels etc.) to waste bank, deposit them and get money or product from them. The waste bank process is illustrated in Fig. 12.5.

Another type of waste bank is ICT based waste bank which is a waste bank application based on web and android systems. The system presents different scheme, in which the waste collection management is conducted by the waste bank committee through an Android application. The system is based startup entrepreneur and placed in Google play store, thus everyone can easily access the application. In this system, the waste bank members make bank account through the application. Waste transaction is recorded through online system which is integrated with the payment system.

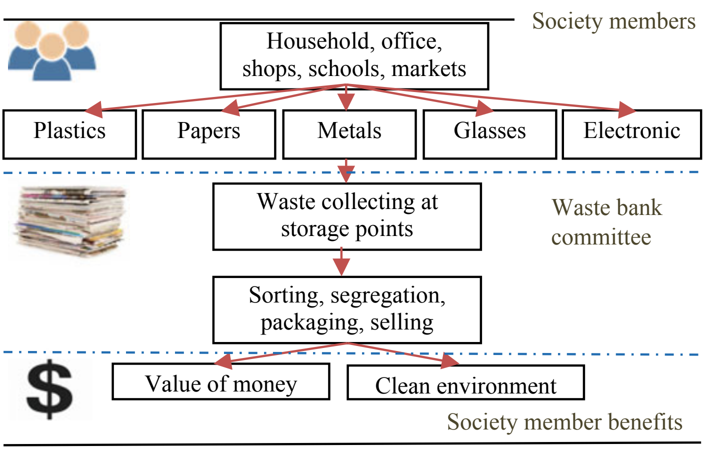

Fig. 12.5 Waste banks process

Fig. 12.6 ICT based waste bank in Indonesia

Fig. 12.7 SMASH online waste banks activities

The following Fig. 12.6 presents some Android application based waste bank in Indonesia.

Figure 12.7 illustrates one online waste banks called SMASH which is developed and managed by millennial generation, with national coverage area (GEnerasi Informatika Kreatif 2019).

The combined waste bank offers effective community participation in conserving the environment, providing better public health sectors, improving economic values of waste, and generating better income to the society.

12.5 Implications of Revised Framework

The revised framework of waste management system has been focused on the potential of animal edible material production and the participation of waste community including scavengers and waste banks. The implications of the revised framework are presented in Table 12.1 as follows.

Animal edible material as part of smart circular waste management or as standalone process is expected to be adopted in Indonesia as part of mature local approach. In general, this approach needs lower investment cost than other treatment technology. In addition, this approach will reduce the waste amount and process time and residual waste from at the beginning stage of waste management cycle. It is

Table 12.1 Implications of the revised frame work

Approach	Implications			Waste
	Social	Economic	Ecological	Reduction
Animal edible material	Positive for odour reduction	Positive for creating job, improving income, material recovery	Positive for producing green, healthy materials	Direct benefits for reducing organic waste
Waste community – Scavenger, waste bank	Positive for properly employed scavenger	Positive for creating job, improving income, material recovery	Positive for clean environment	Direct benefits for reducing non organic waste

convinced that the waste actually is promising future resources not only for human life but also for animal life. However, in term of current waste management, this approach is less adopted due to lack of knowledge and skill. Appropriate facilitation promotion and education from government and its stakeholders (e.g. industry, non-government organization, private sectors, university, and community) could explore the benefits of the strategy.

Regarding the empowerment of waste community, it is expected that wider implementation of waste bank will provides more social, economic and environmental benefits for non-organic waste management process. The reduction of non-organic waste sent to landfill is one good step of nature recovery practice. Some more treatment technologies (i.e. recycling, remanufacturing, remodification) can be further applied to transform non-organic waste into secondary market or secondary processes in waste stream management. However, the adoption of ICT and IoT to enable the integration of waste management system is urgently required in order to meet efficiency of the system, accuracy of information and data performance, and manageability of process, sustainability of resources and improvement of workforce engagement. The roles of ICT and IoT in the future will definitely improve the waste management in a region. For example, a geospatial system could be used to map all infrastructure, asset, locations and coverage area in which the waste management activities are conducted. Through this system, Government or third party stakeholders (i.e. waste buyers, collectors) can monitor the waste management process on time, anywhere, and anytime.

Scavengers could become big bound of waste management in the waste fields. However, working at waste disposal center can be dangerous for scavengers, if they work informally. Government protection and attention through contract labor program could help scavengers to perform safely and productively. Especially for developing countries like Indonesia, if sufficient labor protection, safe technologies and healthy environment are in place to protect scavengers as government labors, more labor intensive can be sustained to reduce waste, to conserve materials and to reduce emission.

Nationally, there are some regulatory and policy decision related to waste management strategies (Aprilia et al. 2013). However, decisions for selecting waste management approaches are often conducted locally and are different among the cities. Local wisdom and phenomenon in a region should be concerned thus the waste management can be optimally suitable with the local environment.

In addition, Indonesian Government through their policy and regulation could provide standardization and accessibility markets for resource or products created from waste, in order to maintain the sustainability of the waste treatment process. As long as the market is available and price standard is freely adjustable to the supply and demand, it is convinced that the revised framework with its adjustment on process and technology can be optimized.

12.6 Conclusion

This research shows some potential opportunities to convert waste into valuable resources through suitable technology and approaches. The revised framework considered local phenomenon and wisdom as an essential part of waste management success factors in Indonesia. Animal edible material components and combined waste banks were found to generate more economic, social and environmental values to Indonesia. However, Governance from the government should provide supports, regulation and policy accordingly.

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Chapter 13
Information Flow System for Chemicals in Products (CiP) with Adequate Attention to the Social Dimension: The Japanese Challenge and the Way Forward

Makiko Kohno and Masahiko Hirao

Abstract In Japan, a new information flow system for chemicals in products (CiP), named chemSHERPA, was initiated in 2016. This system provides the name of a chemical, its Chemical Abstracts Service (CAS) number, and its proportion by weight in each part of a product, combined with legal information covering upstream to downstream companies. ChemSHERPA may be the first major step to control CiP of various kinds, as it incorporates a database other than IEC 62474. However, future steps should be considered. We reviewed the conceptual background for information systems such as chemSHERPA and considered how it could be modified. Most systems stress efficiency, wherein chemical management issues are considered at the beginning of system development; this attitude leads to the circular economy (CE). However, some warnings have been made about the CE. For example, the CE is such a young field with many definitions that there is a risk of overlooking the social dimension. In response to this warning, adequate attention should be paid to the social dimension and construction of a "closed loop", remembering that the disposal of hazardous chemical wastes should be avoided. We examined how chemSHERPA's information content may be improved, especially from a legal perspective focusing on the final waste management. In this context, we analysed legal systems in Japan, the US and EU, and compiled a list of landfill criteria. Finally, we propose a sample list to be added to chemSHERPA. This revision enables the control of hazardous substance emissions, strongly related to the social dimension of sustainability.

Keyword Chemical management · Chemicals in products · Circular economy · ChemSHERPA · Landfill

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Abbreviations

*1: PFOA/PFOS	Perfluorooctanoic acid/Perfluorooctane sulfonate
*2: PFASs	Perfluoroalkyl sulfonates
*3: SAICM	Strategic Approach to International Chemicals Management
*4: ELV Directive	End-of-Life Vehicles Directive
*5: RoHS Directive	Directive on the Restriction of the Use of Certain Hazardous Substances in Electrical Equipment
*6: JGPSSI	Japan Green Procurement Survey Standardization Initiative
*7: JAMP	Joint Article Management Promotion-consortium
*8: CSCL	Chemical Substances Control Law
*9: TSCA	Toxic Substance Control Act
*10: REACH Regulation	Regulation for Registration, Evaluation, Authorization and Restriction of Chemicals
*11: SVHC	Substances of very high concern
*12: RCRA	Resource Conservation and Recovery Act
*13: HSWA	Hazardous and Solid Waste Amendments
*14: CLP Regulations	Regulations on classification, labelling and packaging of substances and mixtures
*15: POPs Regulations	Regulations on persistent organic pollutants

13.1 Introduction

Over 85,000 chemicals are currently produced (To et al. 2018; US EPA OCSPP 2016), with 1000 new chemicals introduced every year (Meng and Liu 2010). Some are so hazardous for the environment or human beings that we recognise the need to control them. Thus, chemical management (CM) systems and laws have a long history in many countries/regions. However, control of chemicals is clearly insufficient. For instance, in Indonesia, mercury poisons gold miners throughout the country, and the threat continues to escalate (Pressly 2013). In the US, PFOA/PFOS[*1], which has an adverse effect on people, was discovered in drinking water, and eight major companies in the PFASs[*2] industry voluntarily agreed to phase out production in 2000 (EPA 2017). In 2017, DuPont settled over 3500 lawsuits for 671 million dollars (Nair 2017).

There are several CM bottlenecks, such as the large number of chemicals, lack of data for risk assessment, and difficulty of regulating consumer products. The so-called "chemicals in products" (CiP) or "chemicals in articles" is one such bottleneck. Chemicals are not always used individually but may be in a product, and in such cases, it seems more difficult to obtain the relevant information. We need information on CiP because of legal requirements, consumer interests, product safety and control, the possibility of the substitution of hazardous substances and end-of-life management (Kogg and Thidell 2010). This information is the essential basis of decisions concerning human safety or the sound environment.

In this situation, the CiP Programme was initiated by UNEP in 2009 and welcomed by the second session of the International Conference of Chemicals Management (ICCM2). On the other hand, some industries, for example, the automobile manufacturers or the electric and electronic (E&E) industry, have attempted to make information flow systems through the supply chain. In this context, a new information flow system, called chemSHERPA, was initiated in Japan in 2016. ChemSHERPA succeeded in the first stage, involving over 10,000 companies as mentioned below, and we should now consider the next step.

As for CiP information systems, some authors have provided overall surveys (Kogg and Thidell 2010; Massey et al. 2008; Becker, Monica Becker Associates Sustainability Consultants 2009; Bengtsson et al. 2011). Most other papers or reports are analyses of the information flow itself or demands from stakeholders. These are based on interviews focusing on a specific field, such as textiles, electronics or consumer products (Fransson and Molander 2013; Kuo et al. 2014; Nimpuno et al. 2011; Fransson et al. 2013; Scruggs and Ortolano 2011). While analysis of information flow or demand is important, the main purpose of the systems is to comply with laws, as described below. Hence, the legal standpoint is also imperative. From a legal perspective, there are two ways in which information systems may develop. One is to redesign the legal system itself. This is necessarily time-consuming, although it deals with the problems at a fundamental level. The other is to re-examine the existing information system without revision of the current legal system. This must be temporary, but can be performed so quickly that it may complement the time gap generated by redesigning of the legal system. In this paper, we choose the latter way, a re-examination of chemSHERPA, and will discuss revising its information content from a legal perspective. That is to say, the aim of this paper is to suggest a revision of the chemSHERPA substances list.

The next section begins with a review of the conceptual backgrounds of CiP information systems: CM and the circular economy (CE). In the third section, we present a brief history of chemSHERPA and describe its characteristics. Then we point out that a missing but essential part of chemSHERPA is the final disposal stage, closely related to the social dimension of sustainable development (SD). In the fourth section, we analyse the legal systems for final disposal in Japan, the US and EU, make some specific suggestions regarding the modification of the chemSHERPA list in the fifth section, which is followed by the conclusion.

13.2 Conceptual Background

In this section, we review the conceptual backgrounds of the information flow systems, not only chemSHERPA but also similar systems around the world. The similar systems include the International Material Data System (IMDS) (IMDS

Table 13.1 Laws/standards included in chemSHERPA and other systems

System name	Industry	Laws or standards included in its database
chemSHERPA	–	CSCL*8, TSCA*9, ELV Directive*4, RoHS Directive*5, POPs Directive*15, REACH Candidate List, REACH substance restrictions, IEC 62474 GADSL
IMDS (2017)	Automobile	GADSL (mainly legislation in Europe, Japan, and the Americas; specifically, about 60 laws/regulations/treaties in about eight countries)
BOMcheck	E&E	IPC1752A [IPC (2019)] (RoHS, REACH Candidate List, REACH substance restrictions, IEC 62474), Battery substance restrictions, Proposition 65

2017) and BOMcheck, as shown in Table 13.1, which are categorised as the industry-specific systems (Massey et al. 2008) or the inter-chain information systems (Kogg and Thidell 2010).

13.2.1 Chemical Management

The primary purpose of CiP information systems similar to chemSHERPA is compliance with CM laws (IMDS 2017). One goal of chemSHERPA (METI 2014), as mentioned below, is the same as that of other similar systems.

In fact, one goal of SAICM*3 is to ensure that "information on chemicals throughout their life cycle, including, where appropriate, chemicals in products, is available, accessible, user-friendly, adequate and appropriate to the needs of all stakeholders" (UNEP 2006). Responding to this SAICM goal, the ICCM2 invited UN Environment to lead and facilitate the Chemicals in Products project, followed by the Chemicals in Products Programme (CiP Programme). The guidance document of the CiP Programme suggests several laws/regulations for selecting chemicals (UNEP 2015), which include the same laws/regulations in the chemSHERPA list. Thus, chemSHERPA and other systems are in line with the CiP Programme.

Note that, from a CM perspective, especially in the SAICM, chemical lifecycles include not only the supply chain, but also final waste management.

Nevertheless, these information systems mainly consider the laws/regulations for manufacturing, or at most for recycling, such as the ELV Directive*4 (in IMDS) or RoHS*5 (in BOMcheck, chemSHERPA). In other words, these systems fail to consider the final disposal stage. Moreover, except for compliance they seem to focus on other aspects. For instance, in chemSHERPA, the cost savings from compliance are stressed (Machii 2017). In particular, it is emphasised that, for CiP management, information transfer is more cost-effective than chemical analysis (Santo 2017). These points seem to imply another background for information flow systems.

13.2.2 The Circular Economy

We assume that the background mentioned above is the CE. The reasons are as below.

We can find over a hundred definitions of the CE (Kirchherr et al. 2017), although there is no commonly accepted definition (Yuan et al. 2006; Ghisellini et al. 2016) because the CE is not a mature concept. Despite this, we can detect common core CE principles from the various definitions. They are the "3R framework" particularly promoting recycling with "system perspective" and "economic prosperity" (Kirchherr et al. 2017; Yuan et al. 2006). In Japan, a policy named "a recycling-based society" has been implemented and this policy is also considered as one of the various forms of the CE (Lieder and Rashid 2016). As the information systems, including chemSHERPA, focus on compliance with laws for both manufacturing and recycling and emphasise economic aspects such as cost-effectiveness, we can mention that they are based on the CE.

Moreover, the CM perspective may be essential to the CE for prioritising or categorising materials for control and retaining them for as long as possible (ECHA 2016; Vanner 2014). Therefore, it seems that CM and the CE are closely related, and this relationship also supports the idea that the CE is another background for the information systems. Furthermore, by stressing cost-effectiveness, these systems seem to prioritise the CE over CM.

13.3 ChemSHERPA in Japan

13.3.1 A Brief History of ChemSHERPA

Prior to 2014, there were two CiP information flow systems in Japan managed by the JGPSSI[*6] (Electronics et al. 2019) and the JAMP[*7] respectively. The former was based on the Joint Industry Guide (JIG) issued by the E&E industry in Japan, the US and Europe, while the latter, issued by the JAMP, was based on the JIG and IMDS (IMDS 2017). In 2012, a new international standard, IEC 62474, was established (Stachura and Stein 2012), and the JIG was transferred to IEC 62474. At that time, the two systems still co-existed, even though both shifted their bases into IEC 62474. Confronted two different standards, the Ministry of Economy, Trade and Industry (METI) developed a next-generation system, and led the JGPSSI and JAMP into this unified system, chemSHERPA. In 2016, the JAMP initiated the formal operations of chemSHERPA (METI 2017). Many enterprises have recently moved from the system managed by the JAMP or JGPSSI to chemSHERPA, and over 10,000 companies draw on application software prepared by a provider. These companies are mainly, but not exclusively, in the E&E and chemical industries.

13.3.2 ChemSHERPA Characteristics

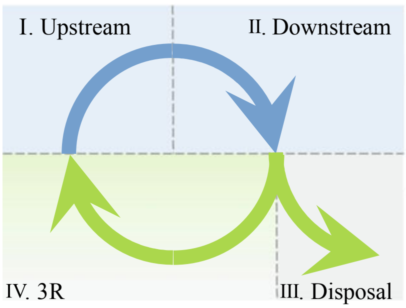
Generally, the chemSHERPA system provides the chemical's name, CAS number and proportion of the chemical by weight in each part of the product, combined with legal information from upstream to downstream companies. We explain some characteristics of chemSHERPA below.

First, some of the goals of chemSHERPA are as follows (METI 2014).

1. This new scheme should make it possible to respond to the regulations for chemicals in products and contribute to the World Summit on Sustainable Development (WSSD) 2020 goal (United Nations 2002).
2. All actors in various industries through the supply chain can use the scheme.

From goal 1, the main purpose of chemSHERPA may be understood to be compliance with the laws (Masui and Matsumoto 2019), as described above. To achieve both goals, chemSHERPA provides a list of declarable substances. This is a list of substances regulated by laws/regulations and industry standards. More specifically, the list currently incorporates CSCL[*8] (Class 1 Specified Chemical Substances), TSCA[*9] (Section 6), REACH Regulation[*10] (SVHC[*11], Restricted Substances), other laws, GADSL and IEC 62474. All laws/regulations and standards are shown in relation to other similar information systems in Table 13.1. We illustrate the relationship between the product lifecycle stages and the regulations included in the chemSHERPA list in Fig. 13.1. Almost all the regulations in the list are for the supply chain (I and II), although some also cover 3R (IV). We could find no regulation focusing especially on Stage III.

Second, chemSHERPA provides two types of information: composition information and compliance information. For the data format, the XML schema of IEC 62474 is adopted. It is expected that information is sequentially transferred from the chemical industry to the component industry and article manufacturers, using the distributed database system, which is different from the IMDS and BOMcheck. In



Stage	Regulations
I, II ↑ | ↓ + IV	CSCL[*8], TSCA[*9]
	REACH Reg.[*10]
	RoHS Dir.[*5]
	ELV Dir.[*4]
	POPs Reg.[*15]

Fig. 13.1 Relationship between product life cycle stages and regulations in the chemSHERPA list. Blue area (I, II): Arterial industry.
Green (IV) & grey (III) area: Venous industry

contrast to these systems, chemSHERPA does not adopt the so-called "full material declaration" (FMD) system.

Third, responsible information handling is expected based on the SC Partnership Basic Guidelines (JAMP 2016), which state that chemSHERPA is not mandatory but voluntary. These guidelines require data transfer without any omission or deletion of information, as well as authorisation before delivery. Consequently, they support and promote the credibility of chemSHERPA.

13.3.3 The Missing Element in ChemSHERPA

What is missing from, but imperative for chemSHERPA? As described in Sect. 13.2, from a CM perspective, we found that information systems such as chemSHERPA neglect the final disposal stage, which is obviously included in the SAICM goals.

From the CE perspective, however, we make two points. First, the goal of zero waste cannot be realised easily by the CE. Recycling will always require energy and create waste and by-products owing to the second law of thermodynamics (Korhonen et al. 2018). Moreover, optimising production systems to close material loops completely requires a rigid coupling of diverse processes of material conversion in different companies and countries, now and in the (far) future. Thus, successful examples of this kind of design are difficult to find at this moment (Skene 2018; Man and Friege 2016). As a result, the CE cannot be accomplished completely, and zero waste is not easily achieved, either theoretically or practically. This means that the final waste management is still required, even if we act for the CE.

Second, the concept of the CE does not always consider the social dimension of the three pillars of sustainability. In an analysis by Kirchherr et al. (Yuan et al. 2006), only 18–20% of the examined CE articles mentioned the social dimension of SD, while 46% referred to the economic dimension. That is, the CE is "virtually silent on the social dimension" (Murray et al. 2017), whereas this dimension is explicit in SD. This may be deemed to be a kind of warning and is closely tied to the first point. Improper final waste handling often generates social issues such as risks to human health or inequalities and regional disparities related to such risks. In other words, in the case of Japan, lacking the social dimension leads to destroying human well-being especially in depopulated areas and expands disparities further. Hence, we should pay adequate attention to the social dimension and construct a "closed loop", remembering that hazardous chemicals disposal is to be avoided remains.

To summarise, there is a risk that the CE itself is unable to cope with social issues accompanied by the final waste management, although waste will be still generated despite the implementation of the CE. Nevertheless, chemSHERPA has no final waste disposal part. Consequently, we believe that we should modify chemSHERPA, adding the final waste disposal part to remedy this shortcoming that may exist even when the CE is implemented. This is the missing but imperative part of chemSHERPA. In the following section, we attempt to analyse each country's disposal law to propose a modification of chemSHERPA from a legal perspective.

13.4 Analysis of Legal Systems

13.4.1 Scope

We analyse the regulations covering final disposal in Japan, the US and EU because these countries are the main target of chemSHERPA. We focus primarily on landfill, as in most countries, landfill is a final step in a hierarchical approach to waste management, where waste should first be reduced, then reused, then recycled, and incinerated with energy recovery and—only if nothing else works—put in a landfill.

We begin with Japan, followed by an analysis of the other countries compared with Japan because it may be impossible to interpret three legal systems in a completely integrated way due to major differences in their structure.

13.4.2 Japan

In Japan, the classification of waste as industrial or municipal is the first step for waste management. In this paper, we refer only to industrial waste because our focal point is B-to-B information flow. Following the classification of waste as industrial or not, we distinguish hazardous waste called "specially controlled industrial waste" from non-hazardous waste.

At the landfill stage, we can find a similar classification of hazard as in waste classification, and some hazardous waste may not be discarded in disposal sites, unless the sites are isolated. This type of hazardous waste almost always in the form of ash or dust, because in many cases in Japan, incineration precedes dumping in a landfill to reduce the volume of waste. The landfill criteria for these forms of hazardous waste allow eight hazardous substances and stipulate their threshold concentrations. The eight substances are shown below (Table 13.2) (excluding sludge). Waste containing one or more of these substances with concentrations above the threshold must be discarded only at isolated landfill sites.

Table 13.2 Substances in the landfill criteria (Japan)

1	Alkyl mercury or mercury and compounds
2	Cd and compounds
3	Pb and compounds
4	Cr^{6+} and compounds
5	As and compounds
6	Se and compounds
7	1,4-dioxane
8	Dioxins and dioxin-like compounds

13.4.3 The US and EU

In the US and EU, waste management systems are similar in some respects, even though they are very different in the overall architecture. In both systems, the classification of waste into hazardous versus non-hazardous is crucial and should be considered at the beginning of the process.

In the US, there are two general categories of hazardous waste. One is “Listed wastes”, including waste from industrial processes or sources (on F & K lists) and unused chemicals (on P & U lists) according to the type of industry. The other is “Characteristic wastes” consisting of four more specific classifications of characteristics.

Landfill facilities are used as the final disposal sites for a large portion of hazardous wastes (EPA 2005) and included under “land disposal” in the RCRA*12 (Directive 2008). The HSWA*13 to the RCRA prohibits the land disposal of hazardous wastes included in the table of “Treatment Standards for Hazardous Wastes” if they do not meet the requirements of the RCRA (European Commission 2018). This means that there are other criteria for a landfill in addition to the categories for hazardous wastes mentioned above. The table encompasses pesticides, organic substances and ten inorganic substances. The number of organic substances and pesticides is so large in comparison with Japanese regulations that we only consider inorganic substances in this paper.

We list inorganic substances prohibited from landfill in Table 13.3(A). Using this table, we could roughly screen waste prohibited from landfill, although such

Table 13.3 (A) Substances in the landfill criteria, (B) comparison with industry standards, and (C) suggested alternatives

(A)

	Ag	As	Ba	Cd	Cr	Cu	Hg	Mo	Ni	Pb	Sb	Se	Zn	Chloride	Fluoride	Sulphate	Cyanide	Others
EU	○	○	○	○	total	○	○	○	○	○	○	○	○	○	○	○	–	(1)
US	○	○	○	○	total	○	○	–	–	○	–	○	–	–	–	–	○	(2)
JP	–	–	–	○	6+	–	○	–	–	○	–	○	–	–	–	–	○	

(B)

IEC 62474	–	–	–	○	6+	–	○	–	○	○	–	–	–
GADSL	S	○	S	S	S	S	S	–	○	○	–	○	–

(C)

For EU	✓	G	✓	IE	IE	✓	IE	✓	✓	IE	✓	G	✓
For US	✓	G	✓	IE	IE	✓	IE	–	–	IE	–	G	–
For JP	–	–	–	IE	IE	–	IE	–	–	IE	–	G	–

In Table 13.3A; (1) EU others: DOC (dissolved organic carbon), TOC (total organic carbon), Mineral oil (C10 to C40), BTEX (benzene, toluene, ethylbenzene and xylenes), PCBs, PAHs (polycyclic aromatic hydrocarbons)
(2) US others: Endrin, other pesticides (total 6) / Benzene, Chloroform, other organics (total 26)
“6+ ” means hexavalent
In Table 13.3B; “S” indicates the inclusion of only simple substances, not compounds
In Table 13.3C; “IE” means IEC 62474, “G” means GADSL, “ ✓” means a substance to be added to the list

prohibitions have various exceptions and these wastes can be discarded in a landfill after appropriate treatment.

In contrast, in the EU, hazardous waste is defined as "waste which displays one or more of the hazardous properties listed in Annex III" in Directive 2008/98/EC (2008). More practically, to determine whether the substances contained in the waste are classified as hazardous, it is recommended to refer to the CLP Regulation*14 (European Commission 2018). In the CLP Regulation, there is a list of 'harmonised classifications' consisting of over 4000 classified substances.

Besides, the Landfill Directive stipulates waste criteria for acceptance of waste for landfill. For instance, there are leaching limit values for waste acceptable at a landfill for inert waste, non-hazardous waste and hazardous waste. The criteria identify 17 components and each limit value depends on the landfill class. The limit values for "the hazardous waste landfill" means that the waste containing some component exceeding its limit value is prohibited from disposal at any type of landfill. Despite the list of thousands of substances for hazardous waste in Annex III of Directive 2008/98/EC, not all of them are prevented from being dumped in a landfill, and there is a list of only 17 components that may not be accepted for the three types of landfill. These components, except for total dissolved solids (TDS), are shown in Table 13.3 (A).

13.5 Proposal

As described above, a landfill is the final disposal facility in the countries/region mentioned above, and they have lists of substances for prohibition or classification for landfill. These lists can be used for information transfer systems including not only the supply chain but also the final disposal stage, as discussed below.

In Table 13.3(B), we show the industry standards applicable to inorganic substances in chemSHERPA. By comparing Table 13.3(B) with Table 13.3(A), we can derive information to revise the list for a specific country, as shown in Table 13.3(C). For example, the third row is for Japan. As for Japan, all inorganic metals, semi-metals and their compounds regulated for landfill are covered by IEC 62474 or GADSL. We need only identify them under both standards, marking as substances for landfill regulation, and no additional list is required. On the other hand, the second row is for the US, and red check marks indicate substances to be added. In other words, Ag, Ba, Cu and their compounds must be added to the list.

Furthermore, IEC 62474 has a dataset named "Reference substances" with a "substance group", for instance, "Ag and its compounds". We could easily modify this dataset by adding missing substance groups, and make a new list, "for landfill". Because IEC 62474 is for the E&E industry, we can make another list for other industries of the 13 elements in Table 13.3(B) or 17 elements in Table 13.3(A) and make it possible for waste handlers to screen the waste for these elements quickly and easily.

The additional list for inorganic substances mentioned above is so simple that stakeholders in the supply chain could understand and use it easily. When waste handlers obtain this kind of information, they can recognise at least the need for treatment of waste for disposal in a landfill. Organic substances can also be added to the list. Table 13.3(C) is just an example of how to modify the list. An additional simple list is also appropriate for manufacturers and does not hinder cost-effective compliance with the laws, which is the main purpose of chemSHERPA.

13.6 Conclusion

We have briefly introduced the information flow system for CiP in Japan, chemSHERPA, and reviewed the conceptual backgrounds of various systems including chemSHERPA and others. We consider that both CM and the CE are the conceptual basis for such systems. ChemSHERPA does not consider the final stage of waste disposal, which was originally expected to be included in the ideal CM system. This weak point could not be remedied even by implementing the CE because the CE perspective might suffer from the same flaw related to the social dimension of sustainability.

We focused on landfill as the final stage of waste management, because landfill is the last step of a hierarchical approach and accompanies the emissions of hazardous chemicals into the environment. We should prevent such hazardous emissions, as they have a negative impact on human health and the environment, generating local inequality or in some cases inter-generation inequity. As a result, we suggest a modification of industry standards or construction of a simple list using the information such as that in Table 13.3(C), containing elements derived from the landfill criteria. The simple list enables quick modification at low cost. If this kind of information is transferred to waste handlers, it will make it possible to prevent hazardous emissions into the environment.

In this paper, we considered only inorganic substances because we compared the US and EU systems with that of Japan, where only a few organic components are included in landfill criteria. On the other hand, the US system has over twenty organic substances, and these cannot be ignored. Thus, we need further consideration of organic substances even though this may result in a substance-by-substance list.

In the case of chemSHERPA, FMD has not been adopted. Even when FMD is introduced, the simple list mentioned above may be used for quick screening and could reduce the importance of the CBI issue.

Moreover, in Japan, as for chemical waste (i.e., not CiP), we have the Waste Data Sheet for waste independent from the Safety Data Sheet (SDS), and SDS is not transferred to waste handlers. In other words, we do not have consistent data sheets throughout the chemical life cycle, even for chemicals. Thus, if the SDS system expanded its range of application, the situation would never change in Japan. In this case, the information flow system reaching waste handlers would be especially significant.

As described above, the primary purpose of these systems is to comply with the laws. The corollary is that, in terms of control of chemicals, the most critical tool may be laws. If the legal system is well constructed, the control of chemicals would work well. Hence, in the near future, we will have to try the other way—redesigning the legal system and combining it with a voluntary information flow system.

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Part III
EcoDesign of Social Infrastructure

Chapter 14
Forecast of Future Impacts of Using ICT Services on GHG Emissions Reduction and GDP Growth in Japan

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Abstract Information and communication technologies (ICTs) can potentially contribute to realizing a decarbonized and dematerialized society through increased productivity in many industries and lifestyle changes. Several previous studies have focused on these environmental impacts of ICTs use by estimating and comparing greenhouse gas (GHG) emissions reductions with and without existing ICT use. However, few studies have estimated the environmental impacts of future ICT use. In this paper, a method is proposed to make scenarios and estimate future environmental and economic impacts of ICTs use on the basis of a computable general equilibrium (AIM/CGE [Japan]) model. The evaluated ICT services are ICT services already in common use and several new ICTs. Two scenarios (baseline and ICT accelerated) until 2030 are set for assessing the environmental and economic impacts of using these ICTs. Model simulation results show Japan's GHG emissions to be about 34 Mt-CO_2eq lower and gross domestic product (GDP) more than ¥33 trillion higher in 2030 in the ICT accelerated scenario than in the baseline scenario. This demonstrates that ICTs will be able to contribute to both economic growth and GHG emissions reduction in the future.

Keywords ICTs · Environmental impacts · GDP · GHG emissions reduction · Scenario · CGE model

14.1 Introduction

The effects of climate change have already appeared in many areas (IPCC Fifth Assessment 2014). To combat climate change and mitigate its effects and risks, the Pairs Agreement was adopted in 2015, and all nations are expected to make efforts to reduce their greenhouse gas (GHG) emissions. In Japan, the target of

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the government in its Intended Nationally Determined Contributions is to reduce GHG emissions by 26% compared with the 2013 level by 2030 (Submission of Japan's Intended Nationally Determined Contribution (INDC) 2015). All sectors are required to make efforts to reduce GHG emissions. For the information and communication technology (ICT) sector, communication traffic through the internet has increased several score times over the past 10 years with the spread of the internet, smartphones, and various ICTs services (Information and communications in Japan WHITE PAPER 2017). Although ICT use causes environmental load in its own sector (e.g., electricity consumption of ICT equipment), ICT can potentially contribute to environmental load reduction in other sectors through increased productivity in many industries, reduction in transportation use, dematerialization of paper and recorded media, and so on (L.1410 2012).

Several researchers have already focused on environmental load reduction effects of ICT use. For example, the Japan Forum on Eco-Efficiency published its Guideline for Information and Communication Technology Eco-Efficiency Evaluation based on life cycle assessment (LCA) methodology in 2006 (The Guideline for Information and Communication Technology (ICT) Eco-Efficiency Estimation 2006). Subsequently, Nagao developed models to estimate the CO_2 emissions reduction effects by ICT use for individual target ICT services. The models calculated CO_2 emissions reduction by multiplying the ICT service penetration rate, scale of the evaluated activity, CO_2 emission reduction rate by using the ICT service, and CO_2 emissions factor for each ICT service, and sum the individual reductions of all 23 target ICT services (Nagao et al. 2015). Then Origuchi improved the previous study by including the consideration of economic equilibriums among sectors, rather than simply summing the individual effect of each service, by applying a static computable general equilibrium (CGE), and assessed CO_2 emissions reduction effects by ICT use throughout Japan in 2013 compared with 2005 (Origuchi et al. 2017). The Global e-Sustainability Initiative published a report estimating the environmental and economic impacts of ICT in 2030 at the global level. The report shows that ICT's own footprint is expected to reach 1250 Mt-CO_2eq in 2030, corresponding to 1.97% of global emissions, while ICT use could enable the world to cut its global emissions by 12,000 Mt-CO_2eq, corresponding to 9.7 times ICT's own CO_2eq emissions. Also, ICT could generate over US$11 trillion in economic benefits per year by 2030 (Global e-Sustainability Initiative and Accenture Strategy 2015).

Needless to say that penetration rates have grown very fast for some ICT services, e.g., online shopping and online banking. Also, more and more new ICT services, such as artificial intelligence (AI) technology, Internet of things (IoT), smart agriculture, and smart medical technology, are being introduced in many industries and our lives gradually. However, few studies have focused on the GHG emission reduction effects of future ICT use. In this paper, a dynamic CGE model is developed to forecast the environmental impacts on GHG emissions reduction by ICT use for future periods. Two scenarios relative to ICT use in Japan until 2030 are assumed based on several forecast reports, and the potential GHG direct emissions reductions effects and economic growth effects caused by these ICT uses are estimated on the basis of the dynamic CGE model.

14.2 Estimation Method

A computable general equilibrium (CGE) model replicates the Input-Output (IO) Tables in a given region as a set of simultaneous equations, and usually covers all goods and industry sectors in the evaluated region. The dynamic CGE model we adopt in this paper is based on the AIM/CGE [Japan] of the Asia-Pacific Integrated Model (Fujimori et al. 2012). The goods in our dynamic CGE model are disaggregated into 40 commodities, and elasticity production is disaggregated into 9 technologies. Under the economic balance, levels of activity in each sector and prices for all goods, services, and production factors are determined by a price mechanism. The equations also include a set of constraints that have to be satisfied by the system as a whole but are not necessarily considered by any individual actor, namely macro-economic balance. Commodities can be referred to the horizontal axis in Fig. 14.5 and equations used in our model can be referred to reference (Masui et al. 2003). In this model, the final demand sector (households) holds the production factors of capital and labor, which are provided to the producing sectors in exchange for income. The income received is applied to purchasing consumer goods and saving. Households maximize their utility in purchasing consumer goods. Saving is converted into capital in the next period. Producing sectors (enterprises) use production factors and intermediate inputs (e.g., energy and raw materials) to produce products and supply them to the market. In doing so, enterprises conduct production activities to maximize their profits on the basis of their production technologies. The supply and demand for goods and production factors are balanced in the market, and levels of activities and the value of goods, services, and production factors are determined through the price mechanism.

When ICT services are introduced into producing sectors and final demand sectors, production efficiency in producing sectors and consumption efficiency in final demand sectors are expected to be improved. It means that intermediate inputs in various sectors could be reduced, and the related market would be temporarily out of equilibrium. Then the dynamic CGE model can balance the demand and supply in each sector on the basis of a price mechanism for each good and production factor. The structure of the CGE model is shown in Fig. 14.1.

The dynamic CGE model in this paper is extended on the basis of the static CGE model in reference (Origuchi et al. 2017). The model calibrated coefficients with the IO Tables in the base year, 2005 (Masui et al. 2003). Equilibrium calculation starts from 2005, and then capital stock in the next year 2006 is decided by capital stock, depreciation, and investment in 2005. Efficiency levels in 2006, such as energy efficiency, are calculated depending on the technology levels of existing capital stock and new capital investment. Then equilibrium solutions in 2006 will be calculated on the basis of the prepared efficiency levels, and the model will run year by year like this. Furthermore, the relationship between fixed capital formation and capital stock is assumed as putty-clay. That means new capital can be introduced in any sector but cannot be changed once introduced. Allocation of the new capital is endogenously decided to achieve the maximum profit in the equilibrium calculation. Figure 14.2

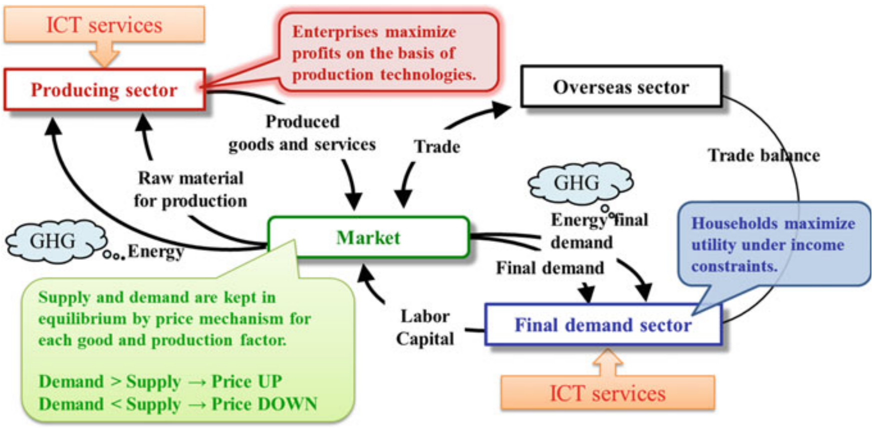

Fig. 14.1 Structure of CGE model

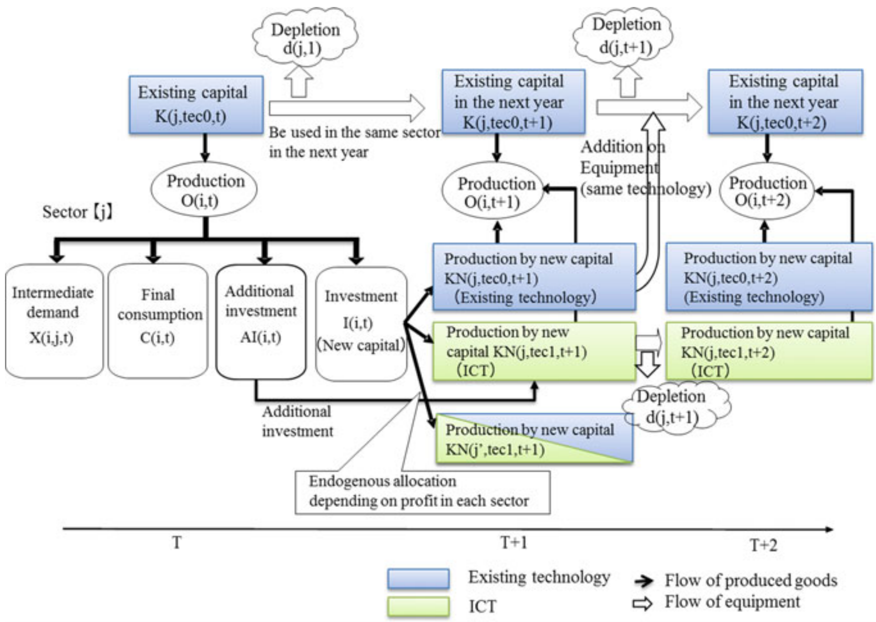

Fig. 14.2 Process of capital accumulation in the dynamic CGE model

shows the process of capital accumulation and productions in our dynamic CGE model. Preconditions, such as future population change, expected economic growth rate, and share of power generation technology are set as given. Also, sensitivity analysis on future scenarios can be done by changing these assumptions. In this model, by introducing the new production investment with ICT services, the ICT services will be realized. However, the retrofitting of ICT services to existing capital is not included. New capital to provide ICT services will be introduced year by year. Expansion on the share of new capital to provide ICT services expresses the spread of ICT services.

14.3 Target ICT Services and Future ICT Scenarios

14.3.1 Evaluation Target ICT Services

In this paper, two groups of ICT services in six industry categories are regarded as the evaluation targets. The first group includes ICT services that are already in common use, such as teleworking and online shopping. The penetration rates of this ICT service group are already relatively high according to some statistical data in Japan (Ministry of Internal Affairs and Communications JAPAN 2005). Table 14.2 lists this ICT service group on which we focused in regular font formatting. The second ICT service group includes several new ICT services, such as AI and IoT in some industries, as shown in bold font formatting in Table 14.2. Even though, now, the present spread of these ICT services is not as high as for the first group of ICT services, they have already started to be used in some industries, like manufacturing and distribution and services, and the effects on GHG emissions reduction are expected to be great in the near future.

14.3.2 Direct Effects Expected by ICT Use

For Group 1, direct effects on GHG emissions reduction caused by ICT use are set the same as those in existing study (Origuchi et al. 2017) and are also listed in Table 14.2. For Group 2, direct effects expected by these ICTs use are surveyed by some forecast reports for future ICT and some use cases that have already been introduced in manufacturing factories or banking (Information and communications in Japan WHITE PAPER 2018). The values of the direct effects are estimated by the total amount of the evaluated activity and the amount reduced by ICT use, and will be fed back to the intermediate input coefficient of the dynamic CGE model.

14.3.3 Future ICT Scenarios

Two scenarios until 2030 are presented to evaluate the impacts by using ICT services: baseline scenario and ICT accelerated scenario. For both scenarios, input data between 2005 and 2015 set the same and are based on statistical data. From

Table 14.1 Pre-conditions in both scenarios

	2005	2030
Population (million)	128	117
Households (million)	49.0	54.7
GDP growth rate	1.2%	1.7%/year
Power supply configuration (renewable percentage) (%)	11	22~24

year 2016, basic pre-conditions until 2030 (such as population changes, expected GDP growth rate, and change in power supply configuration) are set the same and are based on Japan Intended Nationally Determined Contributions (Submission of Japan's Intended Nationally Determined Contribution (INDC) 2015) (Table 14.1).

In order to clarify the effectiveness of the treated ICT services, in the baseline scenario, all technology levels on energy efficiency from 2016 to 2030 are assumed to be fixed at the level in 2015. In the ICT accelerated scenario, penetration rates of most targeted ICT services in Group 1 from 2016 to 2030 are estimated to grow up by linear approximation on the basis of the past data (Ministry of Internal Affairs and Communications JAPAN 2005), since linear approximation could best approximate the past data for almost ICT services. Targeted ICT services in Group 2 are boldly assumed to spread to high levels in our model, since penetration rates of most of these ICT services have not yet been predicted, and the purpose of the paper is to show the potential impacts of ICT use. For most services in Group 2, utilization rates are assumed to be 50%, while for several services which are considered to be spread easily, such as Electronic prescription and smart house, utilization rates are assumed to be 100%. Additionally, the spread of AI technology for unmanned store is not a high prospect, since it strongly depends on lifestyle habits. The final three columns in Tables 14.2 list details of the future scenarios for all targeted ICT services. Investment values to ICT sectors between 2005 and 2020, such as equipment investment or software development, come from a market survey report about the ICT-related market (Nikkei 2016), and the values until 2030 are estimated by linear approximation based on the existing data.

14.4 Results and Discussions

14.4.1 Model Results

In Fig. 14.3, the results show that Japan's GDP in 2030 will be ¥701 trillion in the baseline scenario but ¥734, ¥33 trillion larger, in the ICT-accelerated scenario since more energy efficient activities will be introduced in producing sectors and households by ICT use. In Fig. 14.4, the results show GHG emissions will decrease from 1397 Mt-CO_2eq in 2005 to 1242 Mt-CO_2eq in 2030 in the baseline scenario, due

Table 14.2 Targeted ICT services, direct effects expected by ICT use and future scenario for ICT services

Industry category	ICT services	Effect expected by ICT use	2030 scenarios		
			Index of penetration	Baseline (keep in 2015 level)	ICT accelerated
(A) Finance	A1 Online banking	Reduction of transportation use; reduction of branch banks	Online banking accounts	82.09 million	146.46 million
	A2 Electronic bonds	Reduction of physically transporting bonds; reduction of operation	Electronic bond records	5.82 million	23.71 million
	A3 Cashless settlement	**Cost reduction in management of store business; cost reduction in operation and management of ATMs**	**Utilization rate**	**0%**	**50%**
	A4 Digital technology in banking	**Reduction in office work and customer service in banking**	**Utilization rate**	**0%**	**50%**
(B) Public service	B1 Electronic bidding	Reduction of transportation use	E-biddings	83,000	960,000
(C) Manufacturing	C1 Supply-chain management	Suppression of overproduction; optimization of intermediate distribution and retail sales; reduction of factory and storage space	Utilization rate	40.00%	54.00%
	C2 Matching service for re-use of used-car parts	Reduction of resource use; reduction of office use; reduction of waste	Recycle rate × BtoB EC rate	0.29%	0.45%
	C3 Matching service for re-use of industrial machinery		Recycle rate × BtoB EC rate	1.69%	2.68%

(continued)

Table 14.2 (continued)

Industry category	ICT services	Effect expected by ICT use	2030 scenarios		
			Index of penetration	Baseline (keep in 2015 level)	ICT accelerated
	C4 Matching service for re-use of construction machinery		Recycle rate × BtoB EC rate	1.43%	2.27%
	C5 Matching service for re-use of computers		Recycle rate × BtoB EC rate	2.16%	3.43%
	C6 IoT technology for manufacture	**Productivity improvement by visual control in production line; reduction of lead time**	**Utilization rate**	**0%**	**50%**
(C) Manufacturing	**C7 AI technology for manufacture**	**Productivity improvement by using machine to set up or inspect equipment instead of skilled technician; improvement of operation rate; prevention of human error**	**Utilization rate**	**0%**	**50%**
	C8 Industrial robot	**Productivity improvement**	**Utilization rate**	**0%**	**50%**
	C9 Electronic procurement	**Cost reduction on operation**	**Utilization rate**	**0%**	**50%**

(continued)

Table 14.2 (continued)

Industry category	ICT services	Effect expected by ICT use	2030 scenarios		
			Index of penetration	Baseline (keep in 2015 level)	ICT accelerated
(D) Distribution and services	D1 B to C e-commerce (EC)	Optimization of intermediate distribution and retail sales; unnecessity of storage space and retail shops; reduction in producing CDs/DVDs/newspapers and books; reduction in sales distribution and returned goods delivery	EC rate	5.79%	12.20%
	D2 Online issuing of air tickets	Reduction of transportation use	Rate of online reservation	52.00%	72.00%
	D3 Purchase of tickets at convenience stores		Utilization rate	18.40%	25.40%
	D4 B to B e-commerce (EC)	Reduction of transportation use; optimization of accounting works, intermediate distribution, wholesale, and retail sales	EC rate	29.60%	41.30%
	D5 Online music service	Optimization of intermediate distribution and retail sales; unnecessity of storage space and retail shops; reduction in producing CDs/DVDs/newspapers and books; reduction in sales distribution and returned goods delivery	Online utilization rate	53.60%	53.60%
	D6 Online video service			48.50%	60.00%
	D7 Online PC software			37.00%	100.00%
	D8 Digital books		E-book utilization rate	13.92%	47.90%
	D9 Remote management	Reduction of transportation use	Utilization rate	34.00%	100.00%

(continued)

Table 14.2 (continued)

Industry category	ICT services	Effect expected by ICT use	2030 scenarios		
			Index of penetration	Baseline (keep in 2015 level)	ICT accelerated
	D10 AI technology for demand forecast of food products in retail business	**Reduction of food loss by advanced demand forecast**	**Utilization rate**	**0%**	**50%**
	D11 AI technology for unmanned store	**Labor saving by unmanned operation in store**	**Utilization rate**	**0%**	**10%**
	D12 AI technology for distribution	**Productivity improvement in physical distribution**	**Utilization rate**	**0%**	**50%**
	D13 AI technology for self-driving	**Cost reduction due to the decrease in motor vehicle accidents**	**Utilization rate**	**0%**	**50%**
(E) Medical and agriculture	E1 Electronic medical records	Reduction of paper	Utilization rate	34.40%	74.40%
	E2 Electronic prescription	**Reduction of paper**	**Utilization rate**	**0%**	**100%**
	E3 Electronic medicine notebook		**Utilization rate**	**0%**	**100%**
	E4 Smart agriculture	**Improvement of efficiency on farm work by visual control based on sensor data; labor saving by introduction of robots**	**Utilization rate**	**0%**	**50%**
(F) Infrastructure	**F1 AI technology for electricity demand forecast**	**Improvement of generating efficiency by advanced electric power demand forecast**	**Utilization rate**	**0%**	**100%**

(continued)

Table 14.2 (continued)

Industry category	ICT services	Effect expected by ICT use	2030 scenarios		
			Index of penetration	Baseline (keep in 2015 level)	ICT accelerated
	F2 Smart meter for water supply	**Labor saving on metering work**	**Utilization rate**	**0%**	**80%**
	F3 Smart house	**Reduction of electricity consumption**	**Utilization rate**	**0%**	**100%**
(M) Both category (C) and (D)	M1 Teleworking	Reduction of transportation use; reduction of office use	Percentage of teleworkers	14.70%	34.00%
	M2 TV conferencing	Reduction of transportation use	Utilization rate	13.64%	29.00%

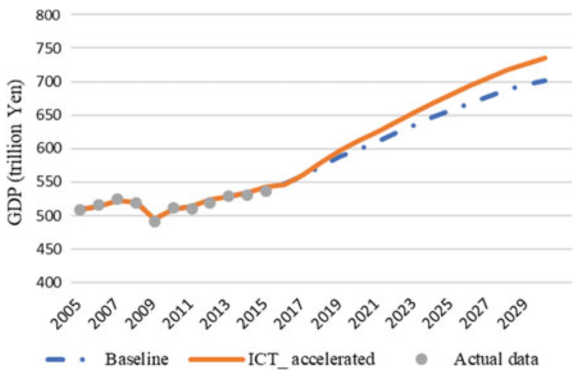

Fig. 14.3 Forecast of GDP growth in each scenario

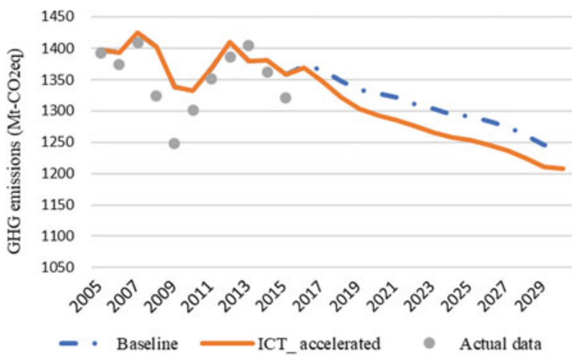

Fig. 14.4 Forecast of GHG emissions in each scenario

to several reasons such as population changes and utilization of renewable energy. In the ICT accelerated scenario, GHG emissions will decrease to under 1208 Mt-CO_2eq in 2030, more than 34 Mt-CO_2eq lower than in the baseline scenario, due to the efficiency improvements mentioned above.

Next, Fig. 14.5 shows the differences in GDP in each sector between the two scenarios. The results indicate that by using ICT, final consumption will increase as income increases. In particular, utility is mostly enhanced in service sectors, so GDP in these sectors increases more than in the baseline scenario. On the other hand, since the commercial margin will be cut by ICT services use in commerce, a singular strong reduction trend is seen in the commerce sector. Next, Fig. 14.6 shows the difference in GHG emissions in each sector between the two scenarios. GHG emissions in many sectors are reduced. Especially, GHG emissions in the transport and post sector decrease largely in accordance with the effect on transport use reduction by using ICT. GHG emissions reductions in the power sector are considered to be caused by the reduction in electricity demand in the sectors that introduce ICT services. For example, for ICT service D_5 online music services, the direct effects caused by its installment include unnecessity of storage space and retail shops, so it can reduce the electricity demand of storage space and retail shops. However, one thing that should be mentioned here is additional electricity consumption will usually

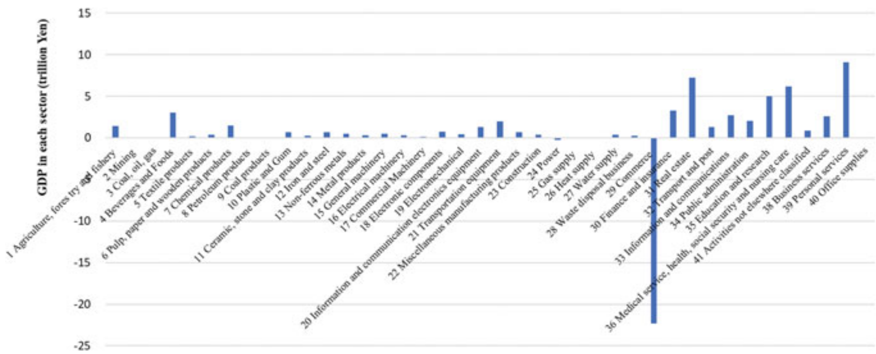

Fig. 14.5 Differences in GDP between the two scenarios in each sector in 2030

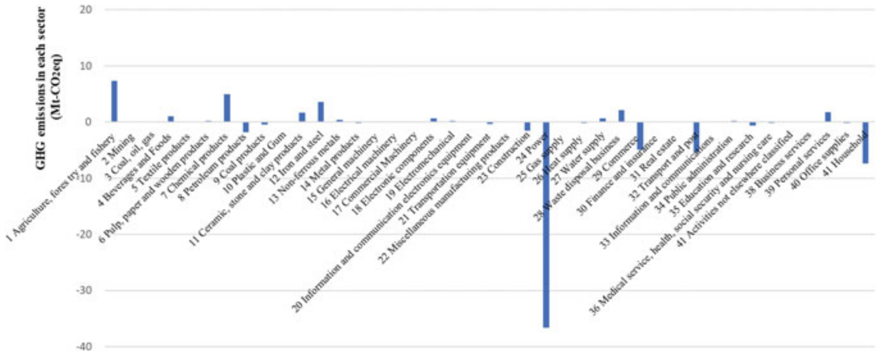

Fig. 14.6 Differences in GHG emissions between the two scenarios in each sector in 2030

occur due to introducing new ICT equipment, such as communication servers and computers. However, since the purpose of this paper is to develop a method to estimate the positive GHG emissions reduction effects by ICT use, the additional electricity consumption is not included here. If the additional electricity consumption is also considered, electric demand will increase depending on the numbers and scales of introduced ICT equipment.

14.4.2 Discussion

Individual GHG emissions reduction effects for ICT services in each industry category in 2030 are also discussed in this paper. In Fig. 14.7, the results show that when ICT services in manufacturing (Category C) are introduced, such as supply-chain management and industrial robots, GHG emissions are most greatly reduced. This is considered to depend on the efficiency improvements in production processes.

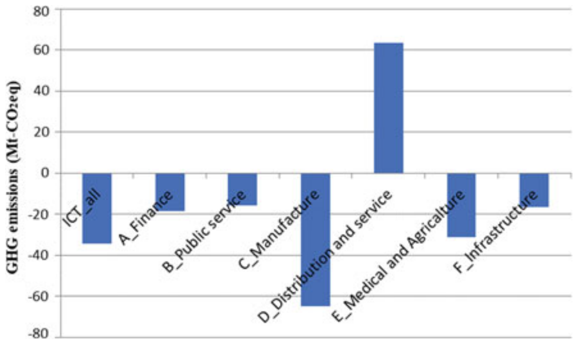

Fig. 14.7 GHG emissions changes in each industry category

On the other hand, in distribution and services (Category D), use of ICT services, such as e-commerce, AI for demand forecast in retail business, or unmanned stores, can drastically reduce labor inputs, and as a result, the surplus labor resources can be moved to other sectors, which can simultaneously push up additional productive activities and cause strong rebound effects.

As a result, GHG emissions will increase when the ICT services in distribution and services are introduced. These results indicate that the faster ICT services spread in manufacturing, the greater their effect on GHG emissions reduction. However, even though production and consumption efficiency will improve, one of the most difficult issues in future ICT use may be how to suppress rebound effects caused by ICT in distribution and services.

Next, Fig. 14.8 shows that GHG emissions intensity (GHG emissions per Yen of GDP) is 7% lower in the ICT accelerated scenario than in the baseline scenario (Fig. 14.8). Similar to the results for GHG emissions reduction effects in Fig. 14.7, manufacturing is estimated to have the smallest GHG emission intensity.

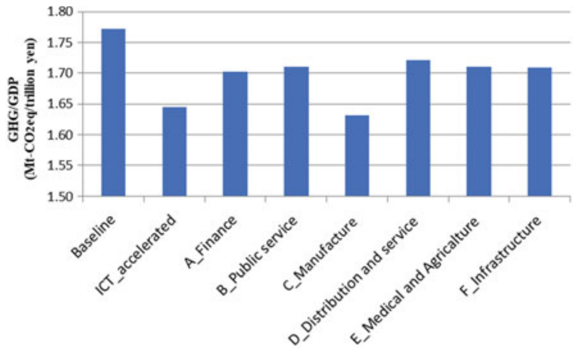

Fig. 14.8 GHG emission intensity in each industry category

14.4.3 Future Issues

As mentioned in 14.4.1, since additional electric consumption caused by introducing new ICT equipment providing these ICT services is not considered in the estimation in this step, future works should include the additional electric consumption in their estimations to grasp impacts of ICT use more comprehensively. Moreover, as this paper aimed to show the potential for GHG emissions reduction effects by ICT use, penetration rates and direct effects expected by ICT services, especially in Group 2, are based on bold assumptions. That means that the results are useful to help us to understand a phenomenon and what "could be", but not absolutely correct answers. In that sense, refinement and sensitivity analysis on penetration rates and direct effects should also be conducted in future works. Furthermore, the model used in this paper does not include the spread of ICT services based on retrofitting. For example, installation of internet service machines to existing convenience stores is not considered in the model, though that may be a common way to introduce ICT services. Only newly established convenience stores installed with internet service machines are considered here. That means the speed of ICT's spread in the model may be slower than that in the real world, and this also should be considered in future works. Lastly, along with the advances made in ICT, various technologies in other sectors will also progress quickly. This paper focused on the impacts by ICT acceleration, but the model may not sufficiently capture actions taken in response to the progress of other technologies. More comprehensive analysis across more sectors should be conducted in future works.

14.5 Conclusion

This paper presented two scenarios (baseline scenario and ICT accelerated scenario) for future information communications technology (ICT) use that are based on several statistical reports, forecast reports, and assumptions by the authors. A dynamic computable general equilibrium (CGE) model was developed to forecast the environmental and economic impacts, including spillover effects, caused by future ICT use. The results show that by 2030 in Japan, greenhouse gas (GHG) emissions are 34 Mt-CO_2eq lower and GDP increase ¥33 trillion higher in the ICT accelerated scenario than in the baseline scenario. That indicates future ICT use can contribute to both GHG emissions reduction and economic growth in the future. However, since rebound effects caused by ICT use are also seen in some sectors, to realize a more decarbonized and sustainable society in the future, it is important to continue the discussion on how to use ICT more efficiently.

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Chapter 15
Methodology for Modeling the Energy and Material Footprint of Future Telecommunication Networks

Lutz Stobbe, Nils F. Nissen, Jan Druschke, Hannes Zedel, Nikolai Richter, and Klaus-Dieter Lang

Abstract This paper presents important methodical aspects in conjunction with the ongoing development of a novel multi-level-model in support of lifecycle environmental assessments of telecommunication networks. The new approach is, to some extent, emulating the OSI-layer model (Open Systems Interconnection), starting at the bottom with the main physical components, followed by product configurations, network architecture and control. On the top layer, the model scales through application and use case scenarios. This complex inventory model furthermore distinguishes between constructive (hardware-defined) elements on the one hand and operational (software-defined) elements on the other. By combining technical data as fixed values with application data as variable values, it is now possible to analyze the causal interaction between different technology generations, network configurations, and utilization intensity. It will allow identifying the best starting point for eco-design and improvement measures. Due to fact that the new methodology is not limited to energy consumption only, it supports a holistic understanding of the environmental impact of telecommunication networks.

Keywords 5G · Inventory · Model · Energy · Material · Footprint

15.1 Motivation

The rapidly evolving mobile network infrastructure is a key element for digitization in modern societies. There is an enormous demand by private and industrial users worldwide for the highest possible traffic capacity (eMBB), low latency (uRLLC), and network coverage (mMTC) (see Fig. 15.1).

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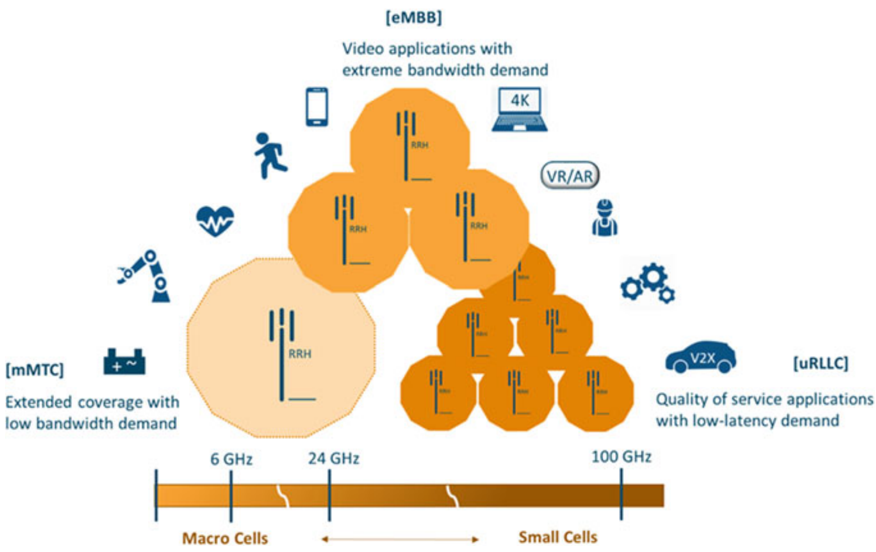

Fig. 15.1 Performance requirements of 5G communication systems based to 3GPP standardization

Currently, fifth generation (5G) mobile communication is underway targeting these high performance requirements. 5G promises to handle 1000 times more data traffic and the question is not just which technologies support this goal, but what amount of energy and material is needed to reach that goal. In theory, there are three technical ways to achieve this improvement in performance (Bjornson et al. 2017):

- More bandwidth (new spectrum incl. mmWave)
- Higher cell density (more access points per area)
- Higher spectral efficiency (massive multi-user MIMO in combination with beamforming).

All of these technical measures as well as a multitude of related technologies and boundary conditions will correlate with the actual energy and material demand of such advanced mobile networks. In standardization, research and development for 5G, energy efficiency is without doubt an important topic. A recent literature review (see Chap. 2) shows that the environmental impact of 5G is addressed only very specifically in research. Frequently it deals with issues for the optimization of energy efficiency, for example in the context of the densification of future cloud (centralized) radio access networks (C-RAN). On top of that, the authors see the need for a sufficiency-driven approach considering the absolute energy and resource consumption of the whole network rather than a pure focus on the efficiency of single technologies (relative energy consumption). More holistic assessments of the total energy and material footprint of geographically implemented networks have not yet been found.

This paper is intended to contribute to a better understanding of the holistic environmental impact of future mobile networks. A series of research questions are being asked which describe the need for a novel modeling of energy and material needs. The following questions require a more consistent answer:

- How do the new 5G network architectures and in particular the concept of the C-RAN affect the overall energy and material demand?
- Which network elements have a proportionally high energy and material demand, and how does this relate to individual technologies?
- What are the interactions and potentials for energy and resource efficiency between transmission power and computation power?
- How does the energy and material impact scale with increasing data traffic, network capacity, and area coverage?
- What are the best technology options for reducing energy and material demand in given network scenarios?
- What is the overall lifecycle impact of 5G networks considering the embedded energy and resources?
- In what order of magnitude and in which direction does the power consumption of telecommunication networks change with an increasing shift of data processing into the cloud?
- To what degree do more efficient technologies compensate for the growing number of antennas and increasing data traffic?

These questions are motivating the development of a new approach for modeling the energy and material footprint of future telecommunication networks. Over the past years, Fraunhofer IZM developed various approaches for modeling the aggregated energy demand of information and communication technology products (ICT) including telecommunication networks and data centers (Stobbe 2015, 2016, 2017). In a previous study (Stobbe 2015), funded by the German Ministry of Economy and published in 2015, the author used a device inventory model with average use patterns for calculating the annual energy consumption. These inventory model based simulations indicated that data centers and telecommunication networks in Germany would reach 50% of total ICT related energy consumption by 2025 (Fig. 15.2).

The telecommunications networks have since then developed significantly in terms of new technology, performance, and applications. Against this background, it seems necessary to develop a much more accurate model for predicting the environmental impact of future telecommunications networks. Moreover, today there is a need to not only determine the energy demand, but also to estimate the production-related use of materials in more detail. Environmental policy makers recognize the utilization of precious metals, rare and critical minerals as similarly important as energy consumption (JRC Science for policy report 2017; SCREEN Project 2016).

In this paper, the authors report about the development of an extended modeling approach. This research is ongoing and part of the research project UTAMO. The task of this research project is the development of a technically precise inventory model for the calculation of the energy and material requirements of current and

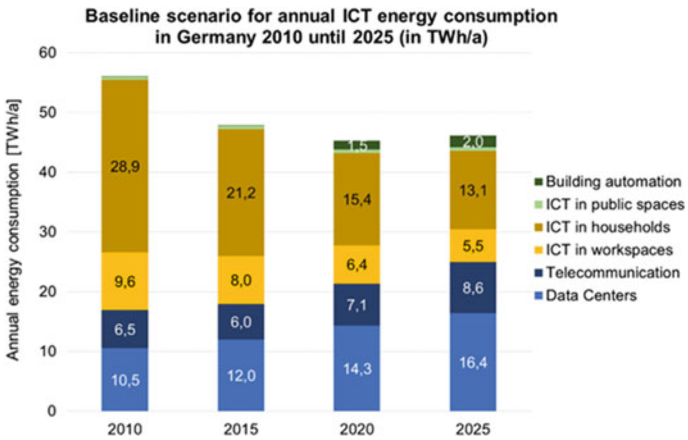

Fig. 15.2 Prognosis of annual power consumption of ICT in Germany

future mobile networks. The German Environmental Protection Agency (UBA) is funding this project, which started in spring 2019.

Due to the fact that the model is still in development, this paper outlines the considerations underlying the methodical approach. The focus of this paper is therefore placed on describing the analytical procedure in determining important environmental aspects of the new 5G technology. The main questions when developing the model have been:

- Which technical features and performance aspects significantly affect the energy and material consumption of 5G networks?
- How can the complexity of existing and future mobile networks be emulated in a technically precise but highly simplified model?
- How to scale the model to an actual geographic reference area and a dynamic development scenario?
- How to handle the diversity of terminology that results from existing and new technical standards as well as relevant scientific literature?

At the end of the paper the authors summarize and discuss the scientific challenges related to the lifecycle-oriented environmental assessment of fast developing and complexly interacting technologies.

15.2 State of Research

Scientific studies that are quantifying the overall energy demand of telecommunication networks and the related data center infrastructure are few in numbers [see Refs. Andrae (2017, 2019), IEA 4E (2019), The Shift Project (2019), Malmodin (2018), Malmodin and Lunden (2018), Peter and Andrae (2017), Hintemann (2017), Kishita

(2016), Lange (2015), Andrae and Edler (2015). Furthermore, despite some product lifecycle assessments, there are even less studies that investigate and quantify the overall material demand of ICT and mobile communication networks in particular.

The existing studies on ICT energy consumption are mostly top-down energy intensity estimates or bottom-up power consumption calculations based on publicly available product stock data (Andrae 2019). These studies differ in product and geographic scope. Their results are difficult to compare. In terms of methodology, these studies often allocate an average power consumption to a representative base case product and multiply this energy with the product stock. There are considerable limitations to the results of this principle approach. The granularity of the product selection for instance determines the accuracy of the result. The active mode power consumption of some product categories such as computers could varies by a view hundred watts depending on the CPU and RAM configuration. Furthermore, the studies are assuming, for the sake of simplicity, usually no real load patterns or differentiated usage patterns. Therefore, increasingly higher utilization and respective power consumption is not adequately reflected.

As a first conclusion, it is justified to say that the existing studies on overall energy consumption of ICT are mostly broad simplifications of reality. Although the older modeling approaches have shown plausible realistic results, they are less suitable as an analytic tool. An advanced inventory model seems necessary for creating and analyzing precise technology- and usage-dependent scenarios.

With regard to the optimization of the energy efficiency of mobile networks, especially with regard to the concrete 5G development, there are a number of recent studies with power consumption models [see references Fiorani (2016), Xiaohu (2017), Nasim (2017), Poirot (2017). A basic power consumption model has been developed in conjunction with the European Union ICT-EARTH project (Imran et al. 2011). This model specifies the main energy contributing components such as power amplifier, baseband unit, cooling, and power supply losses. This power model is quit abstract and not granular enough to calculated energy efficiency options. More recent studies present detailed models that allow, for example, comparison of transmission power with computation power in different network scenarios (Fiorani 2016; Xiaohu 2017). However, these models are also focused only on the analysis of individual technology. None of the models has the goal of calculating a real network implementation. Furthermore, only the energy consumption is modeled. The specific material requirements are not the subject of these studies.

There is another aspect that needs consideration. Past studies did not put the energy and material consumption in perspective to the relative functional performance. The energy performance of a network for instance is a ratio between the amounts of energy used for the transport of a specific amount of data. It makes sense to show the correlation between energy consumption and performance in order to assess the relative environmental impact of telecommunication networks.

In conclusion, energy efficiency and, to a lesser extent, the use of materials are research topics that are currently being addressed in connection with the development of new communication technologies such as 5G. Improving energy efficiency is a general research objective that is pursued for economic reasons to reduce operational costs. Material efficiency such as Gallium, Indium, and Germanium in high-frequency components, is currently not a major research topic.

15.3 Requirement Specifications for the Model

The primary goal of modeling is to calculate the power and material demand of mobile communication networks. The model should be scalable based on specific technology and operating scenarios.

One objective is the analysis of the interactions between different technical options and usage intensities. There is a reasonable assumption that the power and material consumption of future mobile networks will not only be determined by the sum of the individual functionalities, but rather by the configuration of the equipment and the concentration of certain functionalities. For example, there is a trend to pool the functionality of baseband units or routers in larger data centers. Such a measure leads to an improved utilization of the installed hardware and a reduction of redundancy. In addition, shifting the signal and data processing functionality from smaller distributed sites to a larger central data center will improve in most cases the energy balance due to lower overall air conditioning and power requirements.

The desire for a high technical accuracy determines much of the requirement specification for the model. The model should allow the description of different technology and business scenarios using concrete data and assumptions. In addition, the model should reflect as much as possible technical standards, physical principles and theoretical fundamentals of communications engineering. Unlike previous models, the new inventory model should not rely solely on exemplary products and average values. It should be able to differentiate between different functionalities and place them independently of a specific product within the model. This capability of the model will provide the option to analyze the environmental effects of network function virtualization (NFV) and other hardware pooling option in future software defined networks (SDN).

From an environmental analysis point of view, the model should allow the calculation of a time and area specific energy and material footprint. This footprint can potentially be used as the inventory for a full life-cycle assessment, which, however, is not intended to be carried out in the UTAMO project. The model should enable a detailed analysis of the interaction of network components, their configuration and usage intensity on the one hand, with the energy and material requirements on the other hand.

Against this background, the network model should have the following specific references:

- Reference area (defined by geographic boundaries, user density based on demographic data, and other topographic classification such as urban or rural)
- Reference technology (including the technology generation, available radio frequency spectrum, age of equipment, etc.)
- Network topology (including principle network architecture based on existing standards, the functional network devices [equipment] and their component configuration)
- Network performance (including peak or average throughput based on specific utilization profiles, user types, etc.)
- Energy consumption (including manufacturing and use phase, load-/operation mode specific power consumption of individual functionality/equipment)
- Material consumption (allocated to functional components, the material requirement is reported proportionally to the reference year taking into account the total useful life).

It is important to notice that the model is intended and designed as an analytic tool. It should enable the user to calculate scenarios for different technologies and by that help to understand which functionality and technical design choices cause significant energy and material consumption. The focus of the model development is on the goal to calculate real proportions of the energy and material consumption in relation to the individual system elements. It is not so much the goal to determine the consumption absolute exactly. Since the overall effort to cut-off criteria cannot be stated as of now, but the aim is to consider at least 80 or 90% of the energy consumption and material weight. In addition, environmentally relevant materials in small amounts, such as precious metals and selected critical raw materials should be covered. The goal is for the model to achieve a fair level of fidelity.

15.4 Multi-level Model Approach

At this point, the description of the sequential order of the modeling follows. In principle, the inventory model emulates the hardware and architecture of real networks. However, it simplifies its complexity and breaks it down to main functionalities and basic components. There are network technology and specific technical data needed for creating such a model. In addition, assumptions and data about the deployment scenario are required. The scenario assumptions define the goal and scope of the model. A schematic representation of the multi-level model is shown in Fig. 15.3.

15.4.1 Conditions—Application Scenario

The application scenario, or business case, dictates the location, time, and technology reference of the model. The spatial reference (area coverage) can be, for example, the

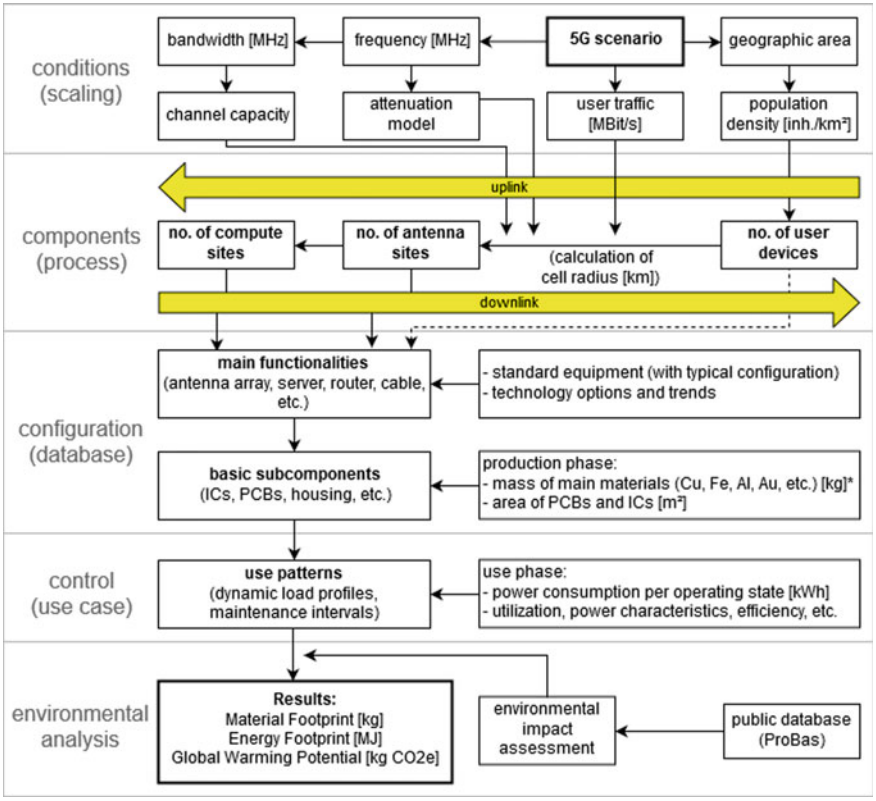

Fig. 15.3 Schematic of the multi-level-model

mobile radio network of a city center or a whole country. It will determine the user density and network utilization intensity. The time reference is also important for environmental assessments, as the energy demand and material demand accumulate differently over a certain time duration. It furthermore allows to assess the network's energy consumption very detailed using dynamic load profiles on an annual, monthly, daily or even hourly basis. The definition of the time horizon is important in the preparation of forecasts, since this also determines technical parameters. The available technology (legacy and new), as well as the available frequency spectrum influences network capacity and defines the network deployment scenario. Based on these conditions and parameters, it is now possible to select the network architecture and create the first process flow. The flowing list summarizes the parameters of the first modelling step:

Area and time scope:

- Total reference area (Germany)
- Model granularity/reference area (km^2)

- Reference years 2018, 2022, 2026, 2030.

Area classification:

- Rural Macro (0–149 inhabitants/km^2)
- Suburban Macro (150–299 inhabitants/km^2)
- Urban Macro (300–2499 inhabitants/km^2)
- Urban Micro (>2500 inhabitants/km^2).

Network scenario:

- Existing 2G/3G/4G networks in Germany (statistical data)
- New 2.0 and 3.5 GHz spectrum antenna sites on existing locations with FWA application primarily
- New 2.0 and 3.5 GHz implementation as Non-Stand-Alone (NSA) with deployment option 3 (3GPP).

Functional units:

- Data rate per area type (Mbps/km^2)
- Data rate per user type (Mbps/UE/CPE)
- Distinction of data and signalling traffic.

15.4.2 Components—Network Architecture

In this step, the basic (communication) channel model similar to a process flow model is created. The channel model emulates a real network architecture of a certain technology generation, its interfaces and network elements. The channel model forms the central axis or the middle level of the inventory model.

The channel model (network architecture) covers horizontally the essential hardware devices along the network layers starting from radio access network (RAN) with individual antenna sites (base stations), over an optical transport network (OTN) all the way to the mobile core network (MCN). The main hardware of these network layers are aggregated as follows:

Radio Access Network (RAN):

- Antenna Array Unit (AAU)
- Radio Frequency Unit (RFU)
- Base Band Unit (BBU).

Optical Transport Network (OTN)

- Optical Transmission Unit (OTU)
- High Capacity Switch (HCS)
- High Capacity Router (HCR).

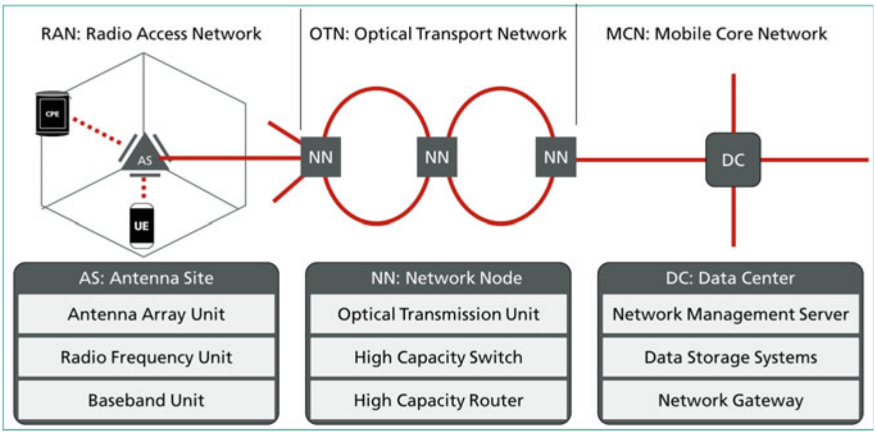

Fig. 15.4 Principle network architecture and elements

Mobile Core Network

- Network Management Server (NMS)
- Data Storage Systems (DSS)
- Network Gateway (NGW).

Figure 15.4 shows the principle network architecture model and the main equipment elements which contribute to energy and material consumption.

The conditions defined in the application scenario (business case) such as the frequency and the intended data traffic per user are used to estimate the cell radius in order to calculate the required number of antenna sites for providing the necessary bandwidth in a given area. The number of compute sites supplying the antenna sites can be derived from there.

There are several architecture options determining the type and location of a network device. Especially in the context of the 5G implementation, there are the option of 5G Non-Stand-Alone (NSA) that share the core network functionality with existing LTE networks or the option of a pure 5G Stand-Alone (SA) network. From an environmental point of view, it is important to analyze and compare several network architectures. Particularly the shifting of computation functionality within the network has potentially strong implications for the energy and material demand. For instance in centralized or so called cloud radio access networks (C-RAN), the pooling of baseband units (BBUs) in large and highly efficient data centers generally offers good energy saving potential.

After defining the network architecture and thus the basic network elements and the interfaces, the individual configuration of these components takes place in the next step.

15.4.3 Configuration—Network Settings

The network configuration is, in the narrower sense, the precise design of the multi-leveled inventory model. At this point, all technical parameters and settings for the selected scenario are specified. This includes, for example, the configuration of the antenna units. The number and type of antennas, the technical specification of the antenna front-end (RF-chain) and the realization of the beamforming (digital or hybrid) are decisions in this context. The model requires technical performance data that correlates with the energy and material requirements of the network elements.

With respect to energy consumption this includes (a) transmission power, (b) computation power, (c) cooling power, as well as (d) power supply losses (AC/DC and DC/DC). With respect to materials this includes (a) standard silicon-oxide chip area, (b) III–V semiconductor chip area, (c) printed circuit board area, (d) material weight of passive cooling, (e) connectors, and (f) material weight of housing.

One of the big challenges is obtaining representative engineering data for all the parameters. Since 5G does not yet have any commercial products on the market, it is necessary to derive the data from standardization documents, technology roadmaps and estimates.

The last methodological step in this context concerns the scaling of the process flow model to the reference area defined in the scenario. This means that the simple channel model is multiplied with the relative number of network elements according to reference area.

15.4.4 Control—Network Operation

The last step in the creation of the network model is the parameterization of the use case. This includes typical traffic load profiles (daily or annual use patterns), options for dynamic load balancing and power management. In conjunction with energy and resource efficiency of 5G, there is in some countries a policy driven discussion about national roaming. This approach would reduce the actual number of parallel network infrastructure.

With regard to a life-cycle type inventory, the energy and material consumption related to the installation (roll-out), repair and maintenance operations should also be accounted for in the model.

15.5 Specific Energy and Material Aspects of 5G Technologies and Architecture

The upcoming 5G networks are based on a set of new technologies including multi-connectivity and C-RAN, massive MIMO and beamforming, as well as small cells and network densification. The following section discusses some environmentally relevant research topics related to these 5G technologies. This discussion of the theoretical interaction between certain technology options and environmental implications are important in the modelling process for creation of application scenarios. As mentioned before, the multi-level model is intended for the use as an analytic tool.

15.5.1 Multi-connectivity and C-RAN

In order to increase coverage, mobile data traffic capacity, and latency, 5G standardization has focused not only on a completely new radio technology (NR) but also on mechanisms to integrate different radio access technologies (Multi-RAT) into collaborative network or Cooperative Multi-Point systems (CoMP) for highly efficient spectrum sharing. These technologies, although providing a considerable performance improvement, are expected to require a considerable higher computation effort by the baseband unit (BBU) and mobility management entity (MME) of the core network. The question of where within the network this calculation takes place ultimately determines how energy and resource efficient it is. There are multiple options. The baseband unit could be positioned as in current LTE networks very close to the antenna unit or further upstream in the metro edge or even the core network. This scenario would require considerable more bandwidth in the fronthaul (in the transport network). A computation of this baseband processing and control signaling within larger data centers (further away from the antenna site) provides a good energy efficiency potential. Larger data center provide the option of higher utilization of existing hardware, reduction of redundancy, and typically more efficient cooling and power supply (better PuE).

The research question in this context is; where is the best position for the BBU and the MME in the network.

15.5.2 Massive MIMO and Beamforming

One strategy to improve spectral efficiency is basically to increase the number antennas and channels. Massive MIMO is an antenna technology that achieves very high data transfer rates and coverage by using tens (32, 64) and hundreds (128, 256) of antennas per sector in parallel. Additional antennas create more channels and help to focus the energy when sending and receiving signals. The transmission power is reduced in this way and the data rate increases. Also, link reliability improves as Massive MIMO allows greater degrees of freedom in the selection of uplink and downlink data streams. This in turn allows extended interference suppression. By combining and synchronizing the active antennas a focused beams can be created resulting in an efficient spatial filtering. The receiver benefits from the signal amplification effect and improved interference suppression. In this way, beamforming further assists spectral efficiency of Massive MIMO and reduces also transmission power consumption.

But Massive MIMO and beamforming have also some potentially negative effects in respect to absolute power consumption and material use. Beamforming is a signal processing procedure creating individual amplitude or phase variations at the transmitter. The mechanism used for beamforming (analog, hybrid, or fully digital) has an impact on energy consumption (Rohde and Schwartz 2016). Depending on the system design and scale of the antenna array, system energy consumption varies (Ali et al. 2017; Roth and Pirzadeh 2017). The Massive MIMO and beamforming concept means that each antenna or every second antenna of the array has a dedicated power amplifier and radio signal processing (RF-chain). In comparison, in current LTE antenna modules one RF-chain is allocated to 8 physical antennas. The much larger number of RF-chains in Massive MIMO will influence not only the total system energy consumption, but the material use as well. Conventional silicon CMOS transistors have limits with regards to high frequency (mmWave) signal processing and amplification. Future high speed and low power devices require higher bandgap III–V semiconductors such as gallium nitride (GaN), gallium arsenide (GaAs, silicon germanium (SiGe), or indium phosphide (InP). The group III elements gallium, germanium, and indium are labeled by the European Commission as critical raw materials (CRM List of European Commission 2017). The group V elements have some toxic potential.

The research question in this context is; what is the best beamforming solution for cmWave and mmWave Massive MIMO antenna arrays?

15.5.3 Small Cells and Network Densification

The last technology concept for improving data traffic capacity is to increase the number of bases stations or antenna sites. This densification of the radio access network is absolutely necessary when utilizing new mmWave spectrum. In Europe the pioneer spectrum and most likely frequency band is 26 GHz. But even in the already auctioned 3.6 GHz spectrum a trend to smaller cell sizes is likely to be seen in order to provide higher data rates to a single user.

The analysis and assessment of the environmental impact of this network densification is complex. There are several factors that increase and decrease the resulting energy and material consumption. In current networks, the main driver for energy usage is the transmission of signals over longer distances from antennas to users. With 5G's smaller cells, less energy is needed for transmission, but computation power increases due to more active antennas and complex signal processing. While it is feasible to assume that for a single antenna system the energy and resource consumption will decrease, the considerably larger number of active antennas as well as antenna sites per area, the absolute energy and material consumption could increase. It is currently unknown in which areas (inner city, suburban, rural area) network densification will take place to what extent. It can be assumed that the cell density will not be expanded to the same extent in all areas. Another factor driving for higher absolute energy and material consumption is the increased demand for broadband transport networks (optical fiber or directional radio). Furthermore, the coordination of the higher number of small cells requires additional computation power.

The research question in this context is; what is the absolute demand for energy and materials due to the expansion of densified networks and to what extent is this potential increase compensated by the improved (relative) energy and material efficiency.

15.6 Discussion of Scientific Challenges

There are a couple of challenges related to this approach. First of all, a considerable technical understanding of existing and future technologies is necessary to create a realistic channel model as the model comes close to simulating real networks. At least in the first stages, a very high level of detail is required to understand which elements have a significant impact. It is expected that only after one or two exemplary calculations it is possible to correct the proportions of the model.

The largest challenge is the acquisition of detailed technical data. Obtaining data for existing mobile networks is less of a problem, as market statistics and product data sheets can be used in this context. This is far more difficult for future technologies and networks. Good sources of information are standardization documents and research reports. Still, concrete data such as device configuration options, exact localization of network components, power consumption values, load profiles and bills of materials are not yet available.

To compensate for the lack of information, physical, electrical, and thermodynamic models are considered to be a viable option for estimating the physical dimensions and power usage of future equipment. These can include the following: characteristic curves for power supplies, signal propagation models, heat management calculations, load profiles, models to estimate the computational effort for signal processing, etc.

The effort and expertise needed to reliably predict and plan the design and functionality of products that do not yet exist is challenging, but a rough estimate to assess the order of magnitude that can be checked against current technical data and roadmap recommendations is reasonably sufficient for modelling the impact.

Since small errors can lead to large deviations when the model is scaled from, for example, a small region to a national level, plausibility checks and iterative corrections are obligatory.

15.7 Summary

The idea of the multi-level model presented in this paper has the potential to act as a tool for planning and optimizing current and future telecommunication networks. The energy and material footprint as the result of the scenario calculations is a valuable source of information on its own, especially when put in relation to national energy and resource consumption. However, it is also a starting point for further life-cycle impact assessment with an extended range of impact categories (e.g. climate change, resource depletion, water footprint, etc.). It could also serve as a foundation for deriving key performance indicators and environmental reports, as well as providing a scientific basis for business solutions, public relations statements and policy decisions.

The methodology and development of a suitable tool for modeling the energy and material footprint of future telecommunication networks are still work in progress as part of the UTAMO project. The next steps will focus on implementing and verifying possible solutions to the challenges discussed in this paper by developing a tool to calculate the inventory of the network model and checking the results against existing data. Thereby the model will be refined at every iterative step.

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Chapter 16
Towards Intercity Cooperation: Comparison of Spatial Transport Energy Efficiency Between Central and Peripheral Cities in Japan

Shoki Kosai and Eiji Yamasue

Abstract Interest in transport energy efficiency in a given spatial area has been increasingly growing as a research topic. Various studies have analyzed the overall association of energy-related indicators with the city form, whereas the compassion of individual city has yet to be fully evaluated. Given the importance of developing the efficient intercity transport cooperation, the consideration of intracity transport situation in the two relevant cities is necessary before determining the intercity travel mode among various modal choices. There is a possibility that even if the intercity public transport infrastructure is developed, automobiles would be the first choice for the intercity travel as long as the public transport system inside of the peripheral cities is not well developed. Therefore, a focus on differences of spatial transport energy efficiency between central and peripheral cities is of significant importance. In particular, the city combination in Japan would be an appropriate case study. In response to the decrease in population, networking the central city with peripheral cities to construct the coordination through the public transport is highly required in Japan to maintain quality of life and sustainable city management. This study first assesses the transport energy efficiency of various transportation modes in the form of transport energy intensity in Japan. The assessed transportation means include walks, bicycles, automobiles, buses and electric trains. The transport energy intensity is obtained on the basis of well-to-wheel (WTW) fuel consumption and energy input for the material structure. Then, this is integrated with the modal split to obtain the spatial transport energy intensity in a given city. This study focuses on 44 cities in Japan and evaluates its relationship with population. Finally, by using the hierarchical cluster analysis, its differences between central and peripheral cities in the major metropolitan area, the sub metropolitan areas and regional urban areas are evaluated from the perspective of the geographical location and city scale gap to

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assist in identifying the specific areas where limitations on constructing the coordination in future are imposed and in providing the strategy depending on the city categorization. It was found that transport energy intensity decreases in the order of automobiles, buses, electric trains, bicycles and walks and the energy input for the material structure significantly affects the transport energy intensity for the small-scale transportation means. In addition, the cities in Japan of lower spatial transport energy intensity were also those with greater population. This trend seen in the case of Japan is matched with the global trend which has been widely reported. In the major metropolitan areas, the spatial transport energy intensity in the peripheral city decreased with distance from the central city. Some peripheral cities more than 30 km away from central cities were identified as the most challenging city combination for constructing the coordination with respect to the spatial transport energy intensity.

Keywords Urban city · Modal share · In-city transport · Metropolitan area · City partnership

16.1 Introduction

In last decades, the expansion of energy demand arising from population increase and heavy industrialization has significantly changed the global energy landscape. Particularly, energy consumption in the transportation sector in 2013 has increased by 2.7 times compared to 1971, while energy consumption in both industry and commercial sector in 2013 has increased by 1.9 times (International Energy Agency 2017). Given the incremental demand of automobile fuels because of the global motorization, the transportation sector consumes 27.8% of the primary energy use worldwide in 2013 (Agency for Natural Resources and Energy 2016). In particular, the energy consumption in the city transportation has been increasingly growing (Wang et al. 2017). A wise energy utilization in the city transportation sector is of paramount importance, since transport is fundamental to the economy and human well-being (Zahabi et al. 2014).

Improvement of energy efficiency in the transportation sector (hereafter referred to transport energy efficiency) has been considered a major approach for addressing energy-related issues in cities. In general, energy efficiency is associated with the relationship between inputs including energy consumption and outputs including costs, environmental burdens and products. An improvement of transport energy efficiency in cities potentially contributes to relieving fossil fuel depletion, mitigating environmental burdens and saving energy costs (Cullen et al. 2011).

Among various types of city transportation, the proper intercity transport cooperation with high energy efficiency is of paramount importance, particularly in Japan. Japanese population in 2050 is highly expected to decrease by 20% compared to 2012 (The Institute of Energy economics, Japan 2015). Population in 63% of residential areas in 2012 will decrease by half in 2050, while merely 19% of residential areas will turn into a non-residential area. Population in central cities in the three major metropolitan areas and the five sub-metropolitan areas is projected to decrease by 15% and population in central cities in the regional urban areas is projected to decrease by more than 20% (Ministry of Land, Infrastructure and Transport 2014). People tend to stay at the attached city where they have lived, even in an inconvenient area. Considering the negative correlation between energy-related issues and population (Yang et al. 2015; Modarres 2013), deterioration of transport energy use in Japanese cities is anticipated due to the decrease in population. Therefore, reconsideration of city transport planning without a forced relocation is required to maintain or improve the transport energy use.

To address this matter, Japanese government published in 2014 Coordinated Core Metropolitan Area Initiative in Japan, in which a partnership is formed between central and peripheral cities (Ministry of Internal Affairs and Communications 2014). Coordinated Core Metropolitan Area Initiative is developed on the two concepts, that is; compactification, or constructing the advanced efficient urban functions, and networking, or connecting the central city with peripheral cities through the public transport network more efficiently (Tsuji 2015). The efficient use of transportation system between central and peripheral cities would highly contribute to intercity cooperation.

According to the aforementioned Initiative, the central and peripheral combination with the greater gap of urban scale should construct the city coordination on a priority basis, since its gap is expected to increase in future. In fact, the intercity public transport system by buses and electric trains has been established between most of central and peripheral cities in Japan. Meanwhile, since the public transport system inside of the peripheral cities is not well developed, automobiles would be the first choice for the intercity travel due to less accessibility to the public transportation in the peripheral cities (Chandra et al. 2013). Before determining the modal choice for the intercity travel, the consideration of intracity transport situation in the urban cities is of importance (Behrends 2012). Given that the modal choice has a significant impact on the transport energy efficiency, therefore, it is of interest to the author to investigate the differences in spatial transport energy efficiency between central and peripheral cities, taking into consideration the geographical location and city scale.

16.2 Method

The methodology in this study consisting of boundary of transport energy consumption, transportation modes, computation of spatial transport energy intensity, case study in Japan, and data collection is presented in this section.

16.2.1 Boundary of Transport Energy Consumption

In the transport energy efficiency narratives, interest in the lifecycle fuel consumption during the transport operational phase has increasingly been growing as a research topic. One of the major lifecycle approaches focuses on the entire fuel consumption during the operational phase from well to wheel (WTW) beyond tank to wheel (TTW) (Fiori et al. 2016). In particular, the WTW assessment has been applied to automobiles (Kosai et al. 2018), electric trains (Washing and Pulugurtha 2015) and bicycles (Melo and Baptista 2017). The other lifecycle approach focuses on the energy consumption during all lifecycle phases including not only operation but also manufacture, maintenance, recycle, and end-of-life (Facanha and Horvath 2007).

This study focuses on the WTW fuel consumption during the operational phase and energy input for the production materials used for body structure during the manufacturing phase. Various studies pointed out the significance of energy consumption at the manufacturing phase among the lifecycle transport stages (Sullivan et al. 2013). Meanwhile, energy input for other life cycle stages including maintenance, recycling and end-of-life, and for the development of transport infrastructure is out of focus.

16.2.2 Transportation Modes

This study analyzes three transportation modes comprising of sidewalks, roadways, and railways used in urban transportation in Japan. Walks and bicycles are assessed for sidewalks. In the roadways, automobiles and buses are selected. For railways, electric trains are selected. The summary of transportation modes and fuel types is presented in Table 16.1.

Table 16.1 Transportation modes

Mode	Means	Fuel type
Sidewalk	Walk	–
	Bicycle	–
Roadway	Automobile	Gasoline
	Bus	Light diesel
Railway	Train	Electricity

16.2.3 Computation of Spatial Transport Energy Intensity

One of the common indicators for evaluating transport energy efficiency is transport energy intensity (Chung et al. 2013; Lipscy and Schipper 2013). Transport energy intensity is represented by energy consumption per mass volume per travel distance.

First, energy consumption for the production of material used in the vehicle body is computed based on the weight and rate of composition of the transportation means and the energy consumption rate of composition by using the following equation.

$$Q_{material} = \sum (Mc_i e_i) \tag{16.1}$$

where, $Q_{material}$ means energy consumption for the production of materials used in the vehicle body, M means a weight of transportation mean, c is a composition rate, e is energy consumption rate, and i is a composition of transportation means.

Due to the consideration of manufacturing phase, the transport energy intensity is changed with the operational duration. The chronological energy consumption during the operational phase needs to be considered. Energy consumption from well to wheel is obtained by utilizing well to tank (WTT) fuel production rate. WTW energy consumption during the operational phase per year is obtained in the following equation:

$$Q_{fuel} = \frac{Ld(1+f)}{k} \tag{16.2}$$

where, Q_{fuel} is energy consumption during the operational phase per year, L is a travel distance per year, d is a calorific value, f is well to tank fuel tank production rate, and k is fuel economy, which is mileage per energy.

This study considers the entire weight of transportation means by calculating the summation of weight of both the passengers and means. It is assumed that the average weight of passenger is 60 kg. Given that the number of passengers is associated with energy intensity for a great scale of transportation means, vehicle occupancy is integrated in the calculation. The entire weight is obtained in the following equation:

$$m = M + 60Pr_{ave.} \tag{16.3}$$

where, m is a weight of both transportation mean and passenger, P is a maximum capacity, and $r_{ave.}$ is average vehicle occupancy.

Then, the transport energy intensity for each of transportation means is computed in the following equation:

$$TEI_x = \frac{Q_{material_x} + TQ_{fuel_x}}{m_x TL_x} \tag{16.4}$$

where, *TEI* is the transport energy intensity, *T* is a lifetime use duration, *x* is transportation means.

Finally, considering the case of average vehicle occupancy and lifetime use duration, the spatial transport energy intensity is computed based on the modal split in a given area by using the following equation:

$$STEI = \sum (TEI_x s_x) \tag{16.5}$$

where, *STEI* is the spatial transport energy intensity and *s* is a modal split.

16.2.4 Case Study

On the basis of transport energy intensity for each of transportation means in Japan, spatial transport energy intensity in various areas in 2010 is evaluated. The central and peripheral city partnership patterns in the major metropolitan areas, the sub metropolitan areas, and regional urban areas for comparison are assessed with a focus on 44 cities. The peripheral cities for each of central cities are selected on the basis of data availability, presented in Sect. 2.5. The summary of cities assessed in this study is presented in Table 16.2.

The relation of spatial transport energy intensity between central and peripheral cities is first monitored. Each of combinations of both central and peripheral cities

Table 16.2 Summary of city categorization

Area	Central	Peripheral
Major metropolitan area	Tokyo	Toride, Matsudo, Inagi, Ome
	Yokohama	Odawara
	Saitama	Tokorozawa
	Nagoya	Gifu, Toyohashi, Kasugai, Tsushima, Tokai, Yokkaichi, Kameyama
	Osaka	Sakai, Toyonaka, Nara, Izumisano
	Kyoto	Uji, Ohmihachiman
	Kobe	Akashi
Sub metropolitan area	Sapporo	Otaru, Chitose
	Sendai	Shiogama
	Hiroshima	Kure, Otake
	Fukuoka	Dazaifu
Regional urban area	Kanazawa	Oyabe, Komatsu
	Shizuoka	Iwata
	Matsue	Yasugi

is categorized on a basis of inter-city distance. The gap of spatial transport energy intensity is computed in the following equation.

$$\Delta STEI = STEI_{peripheral\ city} - STEI_{central\ city} \tag{16.6}$$

The peripheral cities are plotted on the gap of STEI versus the STEI in its associated central city graph.

The relations between central and peripheral cities from the perspectives of spatial transport energy intensity and city scale will then be analyzed. The difference in the city scale is described in the form of population in the peripheral city over population in the central city, referred to as the population gap rate. The less population gap rate corresponds to the greater gap of city scale in this study.

16.2.5 Data Collection

The energy consumption rate of each of the compositions and the fuels is taken from MiLCA (Japan Environmental Management Association for Industry 2005). The data for the fuel production including gasoline, light diesel and electricity (electricity mix in 2010) is taken from Japan Automobiles Research Institute (Japan Automobiles Research Institute 2010).

In the case of a sidewalk, material consumption during the manufacturing phase for walk equals zero and it is assumed that the composition of bicycle is steel. Energy consumption during the operational phase in the both walk and bicycle is assumed to be zero. In the case of roadways, Corolla Fielder (Toyota) represents automobile. The data for automobile is obtained from the author's previous study (Kosai et al. 2018). The data of ERGA (Isuzu Motors Limited) for the bus is taken from Kudo's work (Kudo et al. 2007). In the case of railways, Yamanote line 205 system (JR-EAST) data is taken for the electric train from the report of The Institute of Energy Economics, Japan (IEEJ) (Oki 2002).

The data of modal split, population, and geographical characteristics in 44 cities in Japan is taken from Ministry of Land, Infrastructure and Transport (Ministry of Land, Infrastructure and Transport 2012), Ministry of Internal Affairs and Communications (Statistics Japan 2017) and Geospatial Information Authority of Japan (Geospatial Information Authority of Japan 2017), respectively.

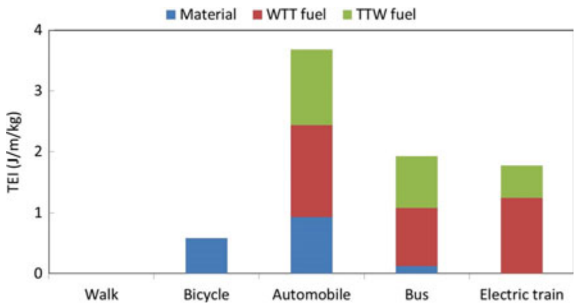

Fig. 16.1 Transport energy intensity

16.3 Results and Discussion

16.3.1 Transport Energy Intensity

Each stage of energy utilization is computed and summed to present lifecycle transport energy efficiency for each of transportation means, shown in Fig. 16.1. The transport energy intensity decreases in the order of automobile, bus, electric train, bicycle and walk. For the small scale of transportation means including bicycle and automobile energy consumption for material structures cannot be simply ignored. It is highly expected that the next generation vehicles such as electric vehicle and fuel cell vehicle require more energy for material structure due to the utilization of precious raw materials (Kosai et al. 2018). Meanwhile, material structure hardly affects the transport energy intensty for the large scale of transportation means including bus and electric train. The significant difference of transport energy intensity at the operational phase between bus and electric train is not observed.

16.3.2 Spatial Transport Energy Intensity

The relationship between spatial transport energy intensity and population is assessed. Each of 44 cities is plotted on the STEI versus population graph. The result is given in Fig. 16.2. To generalize, the cities of a lower STEI are also those with greater population. Higher population areas have developed the sophisticated transport system on a basis of service-intensive city planning (JOURNEYS 2011), where the public transport is fully appointed and a slight movement allows people to reach the destination. That is why walk, bicycle and public transport cover the great share of modal split in those cities and the more efficient transport energy utilization system can be achieved.

This study assesses 44 cites in Japan which are developed with the similar cultural background, prescriptive social norm and concept cultivated under the identical spirit of nation. Besides that, the assessed cities cover the whole Japan from the northern

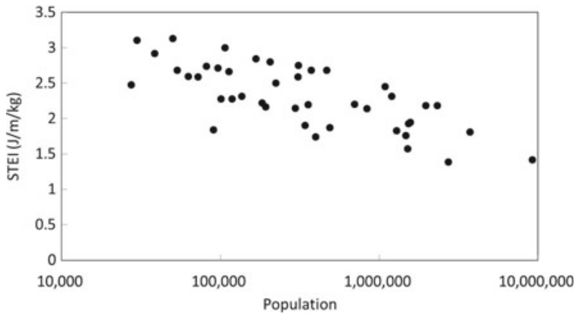

Fig. 16.2 Spatial transport energy intensity and population

areas (e.g. Hokkaido) to the southern areas (e.g. Kyusyu), having different geographical characteristics. Therefore, it might be conceivable to apply the identified relationship of intracity transport energy intensity to the other countries. In fact, the trend that the greater level of population is associated with the lower spatial transport energy intensity in Japan is matched with global trend which has been widely reported (e.g. (Newman 2006)).

16.3.3 Comparison of Spatial Transport Energy Intensity Between Central and Peripheral Cities

The relation of spatial transport energy intensity between central and peripheral cities is monitored. The peripheral cities are plotted on the gap of STEI versus the STEI in its associated central city graph and the name of central city corresponding to the plotted peripheral cities is presented in Fig. 16.3.

In the three area categories, central cities have a more efficient transportation system compared to peripheral cities. Pertaining to central cities, the greater scale of areas in terms of population are much more efficient than the smaller scale of areas including regional urban areas as seen in Fig. 16.2. Meanwhile, pertaining to most

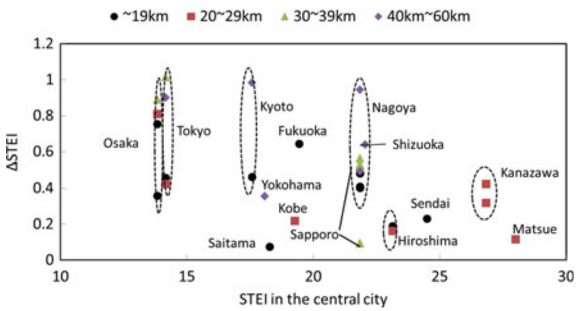

Fig. 16.3 Difference in spatial transport energy intensity between central and peripheral cities

of peripheral cities, significant differences of spatial transport energy intensity are hardly observed regardless of the scale of areas.

The modal split highly affects these trends. The modal split of automobile is much greater in peripheral cities than in central cities, while the modal split of walk, bicycle is much greater in central cities than in peripheral cities. Additionally, the higher modal split of electric train can be seen in the greater scale of areas. The electric trains in central cities in most of major metropolitan areas contributes to 20% of modal split, but in Sapporo, Sendai and Fukuoka in the five sub-metropolitan areas contributes to approximately 10% and the rest cities only less than 5%.

To generalize, the three major metropolitan areas have a wide range of STEI gap between central and peripheral cities. In this area, the further the peripheral cities are away from the central city, the greater the STEI gap is, which indicates that the spatial transport energy intensity in the peripheral city would decrease with distance from the central city. Meanwhile, the sub-metropolitan areas and regional urban areas with the higher spatial transport energy intensity (e.g. Hiroshima, Sendai, Kanazawa and Matsue) have a smaller range of STEI gap even in the middle distance. This would be because the automobile-oriented transport society has been already developed in both central and peripheral cities. In fact, the most cities other than the major metropolitan areas reach 60% of automobile modal split.

Finally, the relations between central and peripheral cities from the perspectives of spatial transport energy intensity and city scale is analyzed. Additionally, a hierarchical cluster analysis was conducted to determine which combinations of central and peripheral cities are clustered together from the perspectives of city scale and the gap of spatial transport energy intensity. The cluster analysis was executed on a basis of square Euclidian distance and Ward's method (Ward 1963). Elbow method was used as guidance in determining the appropriate number of clusters. The result is displayed in Fig. 16.4. It is indicated that there is notable improvement up to around seven clusters, with marginal improvement for the additional clusters.

The relations between central and peripheral cities from the perspectives of spatial transport energy intensity and city scale is presented in Fig. 16.5.

A wide range of STEI gap can be seen at the greatest gap of city scale (cluster #1, #2 and #3). The coordination would be highly required in these clusters.

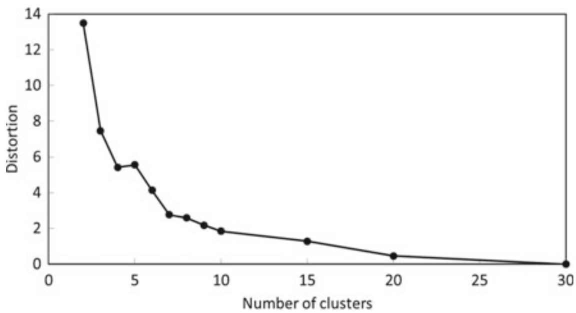

Fig. 16.4 Determination of appropriate number of clusters

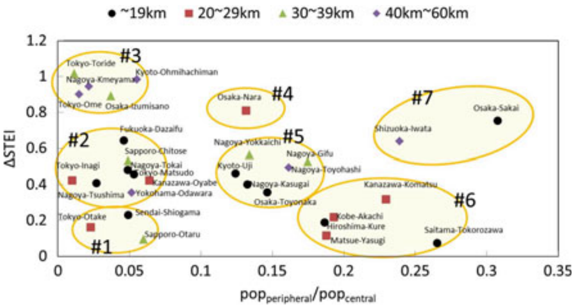

Fig. 16.5 Relation between central and peripheral cities from the perspectives of spatial transport energy intensity and city scale

The cluster #1 is the lowest STEI gap, in which each of the city combination has a significant potential of coordination. The financial promotion of inter-city travel by buses and electric trains would assist in its effectiveness of coordination.

In the cluster #2, many city combinations are connected in the short and medium range, while the exceptional cases can be seen including Sapporo-Chitose (32 km) and Yokohama-Odawara (50 km). The rapid electric train connecting Sapporo and Chitose, where the international airport is, and the bullet train connecting Yokohama and Odawara would contribute to the use of public transportation means for the inter-city travel at the long distance and help the effective coordination.

The cluster #3 is the most challenging city combination for constructing the coordination with respect to the spatial transport energy intensity. All of the city combinations are located in the long-distance range and these peripheral cities are the automobile-oriented society. Although the one rail line connects each city combination, the improvement and promotion of intracity public transport such as buses and the introduction of ridesharing inside of peripheral cities is required for the coordination.

At the greater gap of city scale, city combinations are basically concentrated in the middle range of STEI gap (cluster #4 and #5).

Osaka-Nara is grouped in the cluster #4. Nara city is a capital city in Nara prefecture, out of Osaka prefecture. Therefore, given a great STEI gap from Osaka city, it might be expected that Nara city will independently coordinate the local transport system with surrounding regional villages in the same prefecture. The cluster #5 is composed of many peripheral cities with Nagoya. Despite one of the three major metropolitan areas, the spatial transport energy intensity in Nagoya is inferior to other central cities (see Fig. 16.3). Given the less gap of city scale and the distance further away from Nagoya, it might be better for Yokkaichi, Gifu and Toyohashi to develop the public transport system with surrounding villages. On the other hand, taking the advantage of closer location, Kasugai would still have a potential to coordination with Nagoya.

The cluster #6 and #7 are comprised of city combinations with less gap of city scale.

Particularly, in the cluster #6 Kobe-Akashi and Saitama-Tokorozawa within an intermediate distance range may already independently develop its in-city public transport system. On the other hand, Hiroshima-Kure, Matsue-Yasugi and Kanazawa-Komatsu are the automobile-oriented society. Before considering the coordination, the improvement of public transport system in the central and peripheral cities would be required. In the cluster #7 the difference of city scale in Shizuoka-Iwata and Osaka-Sakai is relatively greater than other combinations, in which the city coordination would not be an urgent matter. Increase in the use of public transport and introduction of ridesharing in the peripheral cities and probably coordination with surrounding villages might be more effective.

The evaluation of relation between central and peripheral cities, from the perspective of gaps of spatial transport energy intensity and city scale, by using the hierarchical cluster analysis would identify the specific areas where limitations on constructing the coordination in future are imposed and would provide the appropriate strategy depending on the city categorization.

16.4 Conclusion

This study has first assessed the transport energy efficiency of various transportation modes in the context of transport energy intensity. The transport energy intensity has been obtained by taking into account the WTW fuel consumption and energy input for the material production. The assessed transportation means has included walks, bicycles, automobiles, buses and electric trains in Japan. Then, the spatial transport energy intensity has been computed on the basis of the obtained transport energy intensity of each transportation mode and the modal split in a given city. This study has focused on 44 cities in Japan and evaluated its relationship with population. Finally, the differences in spatial transport energy intensity between central and peripheral cities have been evaluated from the perspective of the geographical location and city scale to assist in identifying the specific areas where limitations on constructing the coordination in future are imposed and in providing the appropriate strategy depending on the city categorization.

The findings are as follows.

- Transport energy intensity decreases in the order of automobiles, buses, electric trains, bicycles and walks.
- The consideration of WTT energy consumption has a great impact on the transport energy intensity of automobile, bus and train.
- The energy input for the material structure significantly affects the transport energy intensity for the small-scale transportation means.
- The cities in Japan of lower spatial transport energy intensity are also those with greater population.
- In the major three metropolitan areas, the spatial transport energy intensity in the peripheral city would decrease with distance from the central city.
- Some peripheral cities more than 30 km away from central cities with a great gap of city scale were identified as the most challenging city combination for

constructing the coordination with respect to the spatial transport energy intensity. The improvement of intracity transport system in these peripheral cities is highly required.

Meanwhile, the limitations of this approach need to be noted. The energy consumption for infrastructure development is not considered in the analysis. Although the comparison of in-city transport energy intensity between central and peripheral cities is a starting point for discussing the coordination, due to the issue of data availability the modal split of inter-city travel was not considered in this study. The data collection of modal split for the inter-city travel and the application of aggregation approach based on its data to obtain the transport energy intensity of a given corridor would potentially provide the comprehensive insight to the city coordination. In addition, the focus on the spatial transport energy intensity would be considered a macro-level approach, whereas some studies addresses the interaction of transport system between intracity and intercity in a micro-level approach (Ahlfeldt 2011).

In order to improve the transport energy intensity, various implications are highlighted in this study. For the transport energy intensity of transportation means, the control of vehicle ownership by taxation, the establishment of ridesharing legal system and briefing of ridesharing from the perspective of occupancy rate and the promotion of domestic reuse from the perspective would be useful. For the spatial transport energy intensity in cities, the evaluation of relation between central and peripheral cities from the perspective of gaps of both spatial transport energy intensity and city scale by using the hierarchical cluster analysis would identify the specific intercity categorization where limitations on constructing the city coordination in future.

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Chapter 17
Energy Efficiency Within Sustainable Development in Asia: A Boundary Infrastructure and Knowledge Based Frame of Reference

Harald E. Otto

Abstract Effective implementation of energy efficiency measures is becoming increasingly relevant for rapidly industrializing nations, most prominently those emerging in Asia. It is necessary to manage rapid growth of demand and develop new energy infrastructures at the same time. Despite the positive impact of energy efficiency measures in industrial and commercial sectors, there still remain considerable hurdles in practice, preventing them from achieving their full potential. Unfortunately, there is a tendency for problems to be approached from a Western perspective, discounting the differences in the Asian context. In this paper, an alternative reference frame is presented, with a knowledge-based approach taking into account those differences. This is discussed as a first step in regard to energy auditing and one of its immediate explicit outcomes, the energy audit report. This approach is aimed at providing grounds for building an alternative and more adequate perspective on the issue.

Keywords Energy auditing · Energy service concept · Knowledge transfer and exchange · Socio-cultural epistemology

17.1 Introduction

Due to increasing globalization of markets and outsourcing of various services and processes, energy related issues are different in scale and scope for developed nations and developing nations. Statistics on energy consumption and net import of energy, and on energy intensity, show, for example, that nations with emerging and developing economies in Asia, such as China and India, are among the largest energy consumers in the world, but produce only a small fraction of the total global gross domestic product, at a still worryingly high level of energy intensity (cf. (Lo et al. 2015; IEEJ 2018; Enerdata 2019)). Due to its large energy consumption and

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high energy intensity, which are strongly related to its recent unprecedented rapid economic growth, developing Asia is also facing severe environmental pollution, adding another burden to sustainable development efforts.

To effectively address issues of energy conservation and energy efficiency, so-called *energy service companies* (ESCOs) and *energy performance contracting* (EPC) have become the focus of national energy policies in developing Asia. However, despite the market potential of energy service companies and energy performance contracting, and favorable national policies in developing Asian nations, many energy efficiency measures and energy conservation projects in the commercial and industrial sector are simply not implemented. Most literature in the sustainability and energy research area refers to this situation as the efficiency gap or energy paradox (Jaffe and Stavins 1994; Howarth and Andersson 1993), citing as an explanation barriers such as a postulated mechanism that inhibits investment in energy-efficient and cost-effective technology. Although those barriers can be categorized to some extent, most theories and viewpoints are derived from mainstream economics and economics-related organizational and behavioral studies. Hence, suggested solutions are limited, mostly due to domain and discipline specific viewpoints and problem evaluations, but also because of a disregard for the technological, economic, and socio-cultural differences of the Asian context.

To provide a more interdisciplinary approach to the analysis of conceptual and structural barriers to energy efficiency and energy conservation measures in the context and scope outlined above, an approach is presented in this paper which takes into account the business culture and sociology of the work place, while also considering elements of social and cultural epistemology. The objective of these efforts is to encourage problem identification and the development of solutions that are based on a multi-disciplinary and interdisciplinary approach, taking advantage of concepts and a framework that relate to networks of boundary objects and boundary organizations.

17.2 Energy Efficiency and the Asian Context

17.2.1 Energy Efficiency and Related Concepts

Efficiency is a context-dependent notion. In the technical or engineering sense, efficiency is defined as the ratio of output to input, thus quantifying yield achieved compared to resources used. This is different from the concept of effectiveness, which relates to the capability of producing a desired result or outcome (cf. (Mitcham 1994; Feenberg 2002)). Effectiveness describes the degree to which outcomes of programs or strategies match previously set objectives. Of particular interest to program and strategy assessment is the concept of cost-effectiveness, which relates the input of a program or strategy to outcomes achieved. Hence, effectiveness is focused on the achievement of desired outcomes as such, while cost-effectiveness considers the resources required and actually spent in achieving a given objective.

In traditional models and approaches, technology and behavior are somewhat separated when they are being related to energy-efficient machinery or equipment, and the conservation of energy. Conservation of energy is seen primarily as the responsibility of management, with curtailment aimed at reducing either energy usage or costs in general. Such a scenario is not structured so as to gain insight into how members of society, whether they be individuals, households or organizations, perceive energy, or how they plan and actually purchase energy and energy-producing equipment. Nor does it tell us how they perceive energy use per se. Models and approaches that define and study energy efficiency employing economic concepts related to costs, benefits, and economic agents are usually chosen due to their analytical simplicity and usefulness in addressing empirical problems. In particular, adjusted models taking into account the bounded rationality of people (cf. (Simon 1996)) and market imperfections helped to conceptualize so-called market barrier models. Although these approaches are capable of partially integrating some aspects of the technical, social, and economic dimensions, they are still quite limited when it comes to answering questions related to understanding the perception, purchase and use of energy (see also discussions in (Otto 2014; Gillingham et al. 2009; Sorrell 2015; Patterson 1996; Sorrel et al. 2004)).

17.2.2 Historical Perspective and the Asian Context

To a large part, energy efficiency is implemented in practice through the ESCO concept, with energy auditing as one of its central services. It has the potential to provide a significant contribution to energy efficiency realized as a direct transaction between economic actors. From an historical viewpoint, the beginnings of the ESCO concept lie within the development of energy saving businesses in North America in the late 1970s. Although this was directly occasioned by the oil crisis, the origins of this concept can be traced back even further (see (Hansen and Brown 2004)). With an increased presence of ESCOs in the energy service market, the business model and concept of an energy saving project, together with a performance contract, as typically provided, became more widely known and accepted among potential clients. Despite its legacy and success, the ESCO concept arrived surprisingly late in developing Asia. For example, in China the first ESCOs were created in 1998 and such organizations are referred to there as energy management companies (EMCs, see also (Zhang et al. 2008; Wang et al. 2013)). In other Asian countries with developing economies or economies in transition, such as Thailand and India, the first ESCOs were created in 1999 and 1995, respectively. For a more detailed review of the development of ESCO markets and activities, especially in Asia, see (Vine 2005; Okay and Akman 2010; Murakoshi and Nakagami 2009; Kostka and Shin 2013; Sun et al. 2011; Langlois and Hansen 2012; Panev et al. 2014).

Introduction of most energy efficiency measures and instruments in Asia was oriented towards and derived from their counterparts in the USA. Conditions for establishing an energy service industry in developing and emerging countries in Asia always included government support as a first step. This was usually combined with co-operation with international organizations such as the Global Environmental Facility (GEF) founded by the United Nations and the World Bank, the United States Agency for International Development (USAID), or the United Nations Development Program (UNDP) (cf. (Murakoshi and Nakagami 2009; Langlois and Hansen 2012; Panev et al. 2014)). Despite their similarities in structure, the various energy efficiency measures display remarkable differences in their degrees of success. In the case of China, for example, the energy service industry developed rapidly and by 2012 was a USD 8.25 billion market (cf. (Panev et al. 2014)), while in other countries, for example in Vietnam, ESCOs are still trying to establish themselves and become accepted (see (Panev et al. 2014; Pham et al. 2011)).

The services an ESCO provides are usually organized as modules within an energy project and typically include an energy audit, energy-saving design and engineering, energy service contracting, project financing, raw material and equipment procurement, construction and installation, operation, training and maintenance, and monitoring and verification (Hansen and Brown 2004). Within the scope of this paper, the focus will be on the energy audit and one of its immediate explicit results, namely the energy audit report. An energy audit can be seen as an inspection and analysis of energy flows in a process, service, or system. Its aim is to reduce the amount of energy input without negatively affecting the operation, the functionality, or the output. Hence, an energy audit is a means of determining a customer's energy usage profile and energy demand structure, on which basis energy-saving potentials are proposed and energy conservation measures are evaluated. In the commercial and industrial sector, various types of energy audit can be identified. These include benchmarking, walk-through / preliminary audits, general audits, and investment-grade audits. These are all somewhat different from home and residential energy audits, and they require a different set of skills and expertise. The different types of energy audit cover a broad spectrum that ranges from quickly identifying major problem areas (walk-through / preliminary audits) to a comprehensive analysis of the implications of alternative energy efficiency measures deemed sufficient to satisfy the various criteria of customers and possible investors (general audits and investment-grade audits), for more details of which see further discussions in (Hansen and Brown 2004; Thumann et al. 2013).

17.3 Scope and Perspective of Approach

An alternative approach to problem framing will, in turn, allow for novel solutions, processes and outcomes related to energy efficiency efforts within the context outlined earlier. These efforts are related to and interpreted through a knowledge-based perspective. This method not only supports enlargement of the scope of our collective knowledge and insight on how to improve energy efficiency efforts, but hopefully will also help us to find and develop alternative means of getting a better grip on, and eventually mastering, some of the issues and hurdles that are currently prevailing. Under the current frame of reference, the process of energy auditing conducted by experts of an ESCO for a client that is usually an institution or organization from the commercial or industrial sector, and its direct outcome, the energy audit report, can be conceptualized as follows. During the problem-solving process, new information and knowledge is created by a group of individuals with domain-specific understanding related to energy services and management. They utilize their understanding of the current situation (in regard to energy efficiency of the client) and offer possible improvements. The representational structure used for documenting and making available such understanding is usually a text-based document that is enhanced with graphs and tables. This represents the classical construction used for formal reports and office documentation, which, however, is structurally insufficient for representing and communicating the complex nature of underlying knowledge created for the understanding of the client's energy efficiency related situation, and possible improvements. Resulting shortcomings in information transfer and knowledge exchange at the organizational boundary between ESCO and client often severely impede communication, and thus hinder or even make impossible a mutual understanding and collaboration. Additionally, increasing specialization in knowledge and practice creates boundaries where differences in perspectives make a shared understanding and collaboration between various work groups, communities of practice, and organizations from different sectors and professions more and more difficult.

Studies on how barriers encountered on boundaries related to information transfer and knowledge exchange during collaboration across different groups, communities of practice, and organizations can be overcome, while also providing support for building a shared understanding and perspective, led to the notion of boundary objects (Bowker and Star 1999; Bowker et al. 2015; Star 2010). Those boundary objects are considered to be plastic enough to adapt to local needs and the requirements of the different parties employing them, but they are also robust enough to maintain a common identity across different disciplines and perspectives (Bowker and Star 1999). According to (Bowker and Star 1999; Bowker et al. 2015), boundary objects can be classified into ordered piles of objects called *repositories*, objects or descriptions that are called *ideal type* with a less detailed structure serving as a means of communicating and cooperating symbolically, and *standardized forms* that are boundary objects that considerably reduce or even eliminate local uncertainties by devising methods of common communication across dispersed parties. A different classification was proposed in (Wenger 2000), where boundary objects were categorized as *artifacts* relating to models, tools and documents, *discourses* relating to shared common languages, and *processes* relating to shared routines and procedures aimed at supporting and facilitating coordination of dispersed parties. Work on more abstract objects such as narratives and symbolism-based metaphoric boundary objects is reported in (Wenger 2000; Koskinen 2005; Boland and Tenkasi 1995). Based on empirical research from within observed settings in engineering design and product development, and boundary work reported in (Bowker and Star 1999; Bowker et al. 2015), a boundary object categorization relating to the affordances those objects allow at the syntactic, semantic, and pragmatic boundaries has been developed (Carlile 2002). Those affordances, as reported in (Carlile 2002; Carlile 2004), are as follows. At the syntactic boundary, through a shared language, a transfer, that is a communication of knowledge underlying the perspectives, is afforded. At the semantic boundary, creation of a shared meaning that facilitates the translation of perspectives is afforded. At the pragmatic boundary, through the development of common interests, the transformation of perspectives is afforded. Recent work on boundary objects, using the concept of boundary construction, while focusing on the active role of individuals and the function of perspective-giving and taking, is reported in (Holford 2011).

As information transfer, knowledge sharing and creation, and perspective taking across boundaries of groups, communities of practice, and organizations, are still human-centered multi-dimensional activities, socio-cultural factors also need to be considered, as well as technical factors. Although a heavy focus on technical issues still prevails, especially in practice, a tendency towards wider recognition of the importance of the human and socio-cultural dimension seems to be developing, albeit at a slow pace (see also discussions in (Alavi et al. 2006; Ko et al. 2005; Szulanski 1996)). Within such an approach, the author argues, progress can be made by overcoming communication hurdles and interpretative barriers, which in turn can be achieved by taking a fresh look at the problem space and the possibilities afforded by the approach. This, in turn, can be facilitated by providing an epistemology oriented and cross-disciplinary reference frame.

17.4 Toward a Shared Perspective and Understanding at the Boundaries of Intersecting Social Worlds

17.4.1 Outline

The concept of energy efficiency, with its processes and instruments, has been designed and developed in the West. This is a context that is quite different in its quality and level of technological and economic development, and which also varies considerably in its socio-cultural nature and structures, compared to that in Asia, and in particular in nations with emerging and developing economies in Asia.

As outlined earlier, various problems encountered during the realization of energy efficiency measures are usually approached from a Western perspective, discounting the differences of the Asian context. In what follows, an alternative reference frame, taking into account those differences, is presented and discussed as a first step in regard to energy auditing and one of its immediate explicit outcomes, the energy audit report. This should provide grounds for a more adequate perspective, building on the issue.

17.4.2 The Technical and Economic Dimensions

One disadvantage of its legacy is that energy auditing is still approached from the problem-solving perspective of the 1970s using the approach of first-generation methodologies, which is aptly expressed in (Rittel 1984), p 322 as "… you work with your client to understand the problem; then you withdraw and work out a solution; then you come back to the client and offer it to him, and often run into implementation problems because he doesn't believe you." The main reasons, among others, behind this unfortunate situation are, as explained in (Rittel 1984), that the deontic judgments and perspectives used to frame a problem and create the solution remain mostly hidden from the client. Also people seem to be more receptive to a solution when they have been involved in its generation. A more adequate approach to problem-solving in actual practice is to exploit the symmetry of ignorance (cf. (Rittel 1984)), that is try to synthesize different perspectives of a problem and generate possible solutions, rather than just one solution, so that the solutions represent an informed compromise among all the conflicting requirements and interests of multiple stakeholders. To make this effective, domain knowledge, interests, and the concerns of those who are the owners of the problem and those who are contracted from outside to contribute to the solution all need to be considered, and the parties need to collaborate and share their perspectives and expertise. In the given context, this requires that energy auditing and knowledge related processes such as information transfer, knowledge exchange, and sharing of perspectives are supported by objects and structures that help transcend related syntactic, semantic, and pragmatic boundaries (see again, for example (Carlile 2002)). One promising approach in this direction is seen as restructuring and replenishing the process of energy auditing and its documented outcome, the energy auditing report, with a system of boundary objects, which in turn supports the development not only of a shared language and meaning but also common concerns and interests. Here, a straightforward and natural way is to employ a well-structured form of the concept of energy service. Note that this energy service concept, as discussed in the following in regard to boundary objects, should not be confused with the energy audit that by itself is also considered a kind of energy service, and which is provided by energy service companies as discussed earlier. Unfortunately, energy service is still a concept that is defined and used in various, not always consistent, ways, but which was rarely referred to until the 1990s (cf. (Fell 2017)). In particular there is still a wide gap between conceptualizations in the technological and economic field and those in the socio-psychological fields. In the technological and economic field, industrial and commercial energy services are in many cases explicitly linked to electrical, mechanical, and bio-chemical applications along with residential heating and lighting, and public transport. By contrast, in socio-psychological fields, the dominant focus of energy service related studies is aspects of human well-being, welfare, and living conditions, sometimes to the extent that industrial and commercial aspects are entirely omitted (see also discussions, for example in (Morley 2018; Kalt et al. 2019)).

However, as correctly pointed out in most of the recent literature on the energy service concept, people are interested in and use energy not for its own sake, but for the services it provides or enables together with other inputs and technology, to achieve certain goals and ends. Recent developments in structuring, defining, and conceptualizing energy services (as reported and discussed, for example in (Fell 2017; Kalt et al. 2019; Jonsson et al. 2011)) provide promising definitions and frameworks that could be used to translate the energy service concept into a boundary object used for energy auditing and the energy audit report. It can be structured to be plastic enough to adapt to the needs of the various parties employing it, while retaining its overall identity and common understanding. It could also function as a kind of metaphoric boundary object (see again (Koskinen 2005)). If it has a weak, less developed structure, it may still support the coordination and sharing of a tacit, more general understanding and perspective, while, if it has a relatively developed and thus stronger structure, it can support a more explicit coordination and sharing of concrete knowledge and perspectives. This variation in the degree of structural concreteness is an especially useful feature in overcoming some of the pragmatic boundaries in the Asian context. In vertical cultures (details are discussed in the next sub-section) the processing of information takes place according to the hierarchical structure within all institutions and organizations, and professionalism is not usually permitted to influence the relationship between educational background and actual job occupation. It is usually the superiors who have first access to documents and information considered important. However, those superiors may not necessarily possess the technical knowledge and expertise actually necessary to share (as a client) the perspective of the external source, that is, the energy service company.

The approach as outlined could also support information transfer and educational efforts from boundary organizations such as energy service company associations, which still face serious hurdles in many emerging and developing economies in Asia. For example, elements of successfully compiled energy audit reports which pertain to externalized knowledge relating to energy services could be collected and used to form another boundary object, namely repositories of objects that are indexed in a standardized fashion. Those could then be administered by the energy service company associations to support various information and knowledge intensive processes ranging from energy efficiency awareness campaigns for the industrial and commercial sectors, and seminar-based education with practice relevance, to the forming of communities of practice. However, these approaches also need to take into account the socio-cultural dimension of the Asian context, where individuals are more sensitive to context-specific information (see also discussion on contextualism, elsewhere in this paper), in particular when it concerns information about the organization, community, or group they belong to. Those circumstances have a considerable impact on attention, comprehension, and finally efforts to translate this information into knowledge and action (see also discussions in (Kostka and Shin 2013; Tian et al. 2017; Zhang et al. 2018), and the relationship with uncertainty avoidance in (Hofstede et al. 2010; Trompenaars and Woolliams 2003)).

Within the economic and financial settings, production and documentation of economic knowledge are used to provide an informational background, required to make economic and financial decisions. They are used not only to study, analyze, and organize economic realities using economic concepts, but also to reduce uncertainties along paths of economic activity (Knorr Cetina and Preda 2001; Preda 2002). Within the given context, one major issue is knowledge fit in respect to the concepts employed and the information contents and representations chosen for producing and documenting economic knowledge. Here a means is required to convey correctly and adequately the (shared) meaning of energy efficiency investment to different actors from the commercial, industrial, and financial sectors. For example, considering market descriptions in developing Asia, there are differences in environmental regulations and widely offered government energy subsidies to enable highly competitive manufacturing, and these need to be accounted for in action-relevant information provided to economic actors.

Also, there is a desire for much shorter periods of investment payback and for shorter contracts, since economies are often based on the five-year plans which are still in place in various Asian regions, and a large number of state-owned enterprises still exist, with their performance evaluation linked to those centrally planned economies. This environment does not fit the typical time frame considered for EPC within energy efficiency investments in most Western developed economies (cf. (Lo et al. 2015; Kostka and Shin 2013; Zhang et al. 2018)). Which type of information to include within the economic knowledge is also interrelated with the socio-cultural dimension of the Asian context. For example, information related to energy efficiency investment should be more inclusive (see contextualism and tolerance for ambiguity in the next section), instead of focusing exclusively on a particular actor's individual situation (usually that of an ESCO client), as is typically done when knowledge is created and compiled for a traditional (investment grade) energy audit report.

17.4.3 The Societal and Cultural Dimensions

Besides the technical and economic aspects, additional factors relating to social and cultural value dimensions need to be considered in order to gain support for the creation of a shared understanding within the context of energy efficiency in developing Asia. This will also make boundary objects and organizations within a wider boundary infrastructure usable and effective in practice. Societal and cultural values and norms, which have been defined as "the collective programming of the mind that distinguishes the members of one group or category of people from others" ((Hofstede et al. 2010) p 6), with culture being to society what memory is to an individual (Triandis 1995), are essential elements in understanding the dynamics and behavior of groups and communities of practice in their interactions within and across systems and organizations.

Here societal and cultural norms refer to the value systems which are shared by most groups within a nation. In turn, societal and cultural values are described as broad or general tendencies to prefer certain states of affairs over others (cf. (Hofstede et al. 2010)). Hence, culture refers to those values at the collective level in regard to societies as a whole. Note that the degree of cultural integration may vary between societies, though most groups and communities of practice within a society share a basic set of common characteristics with other groups and communities of practice (see again (Hofstede et al. 2010; Trompenaars and Woolliams 2003; Triandis 1995; Triandis 1998)). Besides external influences such as trade and investment, and ecological influences relating to geographic, demographic, economic, and historical factors, societal and cultural values and norms have a fundamental impact on how institutional and organizational structures are built and operated. This will relate to legal systems, firms, markets, educational institutions, and professional associations. From a knowledge-based point of view, societal and cultural values, norms, and patterns also have a considerable impact on how knowledge is created, organized, and transferred and exchanged (see also (Nonaka and Takeuchi 1995)) at the societal, institutional/organizational, and individual level. In the following, the nature and relevance of these issues are addressed within the context of energy efficiency in developing and emerging economies in Asia.

Next, a very brief overview will be given of the cultural values considered to have a significant impact within the context outlined earlier. These are the degree of interdependence a society maintains among its members and the extent to which individuals accept that power in organizations and institutions is distributed unequally. The tendency towards collectivism within the collectivism/individualism value dimension indicates a preference for a tightly knit social framework in which individuals can expect that their clan or in-group members take care of them in exchange for loyalty to the group (Hofstede et al. 2010). Research work reported in (Oyserman et al. 2002) shows that collectivism is associated consistently with interpersonal patterns of interaction, cognition, and self-construal. In contrast with collectivism, individualism demonstrates strong preferences for a loosely knit social network. Here, individuals within society value independence and self-reliance, while advocating and promoting support of their own interests and goals over those of others (Hofstede et al. 2010). Societies that are considered to demonstrate a large power distance in their culture are characterized by their members accepting unconditionally a rigid and strongly organized hierarchical order. This, in turn, is reflected in extreme inequalities in power. In societies demonstrating low power distance cultures, members strive for power equalization, and constantly demand justification for power inequalities (Hofstede et al. 2010). Note that the dimension of power distance as described in (Hofstede et al. 2010) is similar to the value dimension of vertical/horizontal cultures as reported in (Triandis 1995; Triandis 1998) (see also (Shavitt et al. 2011) and the note in (Hofstede et al. 2010) p 486). Hence, those two cultural value dimensions will be used interchangeably in this paper.

Although most approaches, processes, and organizational forms relating to energy efficiency, such as energy auditing, ESCOs, energy service related contracting, and ESCO associations (as pioneered and widely implemented in the West) have been adopted in Asia, the course of development, still in progress in many Asian regions, and the results achieved so far, are considerably different in nature and extent from their counterparts in developed Western nations. For example, the establishment of professional associations has a long history in Western cultures. Those organizations sit in the middle between government and the industrial and commercial sectors and are an important element within a wider boundary infrastructure. They further, among other things, knowledge provenance, provision, distribution, and interaction at the boundaries, while also supporting in many ways professionalism and communities of practice. However, unfortunately, as in the case with many ESCO associations in developing Asia, development and translation into practice of these characteristics and cross-border functionalities have not been achieved yet. Moreover, in cases where the role of an ESCO association is actually taken over by a ministry section or department of the government (cf. (Murakoshi and Nakagami 2009; Langlois and Hansen 2012; Pham et al. 2011)), it is highly doubtful that those hallmarks of professional associations can actually be achieved.

Development of professionalism and preferences, and respect for individual endeavor and expert decisions, are mostly found in individualistic cultures. Also the acceptance of professionalism can be expected to be much higher in societies where individuals at different power levels feel less threatened. In such a cultural context, where probably a loosely knit social structure is prevalent, there is also usually more trust and a tendency towards further imposition of laws and regulations. These socio-cultural conditions stand quite in contrast to their counterparts in vertical collectivistic Asian cultures where large power distances mostly still prevail. Interpersonal and inter-organizational interaction, and thus knowledge exchange and perspective taking at departmental, organizational, and sector-specific boundaries, are also somewhat impeded in collective societies with large power distances. In such societies, information disclosure is restricted as much as possible, in order to avoid conflict, reduce open competition, and preserve the prevailing power structure and the necessary security. This is also consistent with the concerns of collectivists for those closely involved with them, namely the in-groups, co-workers, organizations, etc. they belong to, rather than external parties.

Knowledge created by individuals is embedded in different forms in documents, routines, tasks, processes, and organizational structures, which in turn contribute, among other things, to the formation of perspectives and understandings within social worlds and communities of practice. As, in the end, it is individuals who create knowledge from information and context, and also transfer and exchange both information and knowledge, culture-related preferences for certain elements of the cognitive style should be taken into account, as those have an impact on the effectiveness and efficiency of knowledge-related processes.

In Asia, particularly in East Asia, an holistic thinking style is prevalent, which combines with a tendency to perceive causality in the entire context of behavior. In the literature (Markus and Kitayama 1991; Norenzayan et al. 2002), this is referred to as *contextualism,* as contrasted with *situationalism*, and leads to quickly analyzing and recognizing pieces of information that are becoming part of a larger whole in an associative sense (cf. (Nisbett et al. 2001)). This stands in contrast to the predominant tendency in the West, where causality of behavior is located in the individual and analytical thinking is preferred over holistic thinking, with the latter requiring pieces of information to first be retained and scrutinized (gradual piecemeal-based approach), before any contribution to forming new knowledge can be attempted (cf. (Nakamura 1985)). Another element of cognitive style common in many Asian cultures, namely a tolerance for ambiguity, was found to be instrumental in supporting processes related to tacit knowledge and complex, organizational knowledge (cf. (Szulanski 1996; Nonaka and Takeuchi 1995; Nonaka and Takeuchi 1996)). Another element of cognitive style, so-called *signature skills* (cf. (Leonard 1995)), is found mostly in vertical individualistic cultures in the West. These skills are associated with an individual's task-related preferences regarding the approach and method used to frame and solve a problem, and thus they represent an important means of distinguishing oneself from others. Especially within the context of domain experts and field specialists, these signature skills are highly respected and valued.

17.5 Conclusions

Various problems encountered during the realization of energy efficiency measures are usually approached from a Western perspective, discounting or neglecting to a large part the differences in the Asian context. In this paper, an alternative reference frame has been presented, in the form of a knowledge-based approach taking into account those differences. A first step has been discussed in regard to energy auditing and one of its immediate explicit outcomes, the energy audit report.

Taking into account the current reality of practice, it is reasonable to believe that most ESCOs in Asia are still overburdened and out of their depth regarding the energy efficiency measures as identified by energy audits, and the actual implementation of and contracting for the same. Thus a more realistic interim approach here, and one that would deliver more effective results, might be to consider within a wider boundary infrastructure yet another type of boundary organization besides the ESCO association, one which specializes in knowledge translation and brokering. In most Western nations with developed economies, similar types of such organizations are already employed, and they help in crossing boundaries between science, policy-making, and different industrial and commercial sectors. However, considering the rising awareness and economic importance of knowledge creation and exchange, it is somewhat surprising, and at the same time worrisome, that, in the context of energy efficiency, and in particular within the context as discussed in this paper (see also (Nolden et al. 2016)), this situation still seems to be in an underdeveloped stage from both a theoretical and a practical viewpoint.

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Chapter 18
Study on the Quantitative Evaluation of Greenhouse Gas (GHG) Emissions in Sewage-Sludge Treatment System

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Abstract Global economic development has highlighted the issue of climate change, which is one of the most important environmental issues plaguing human beings. It is widely agreed that excessive greenhouse gas (GHG) emissions are important factors contributing to global warming. Many countries have formulated corresponding GHG emission reduction plans to deal with climate change issues. An important GHG emission source is released from sewage-sludge treatment systems. However, there has not been a comprehensive quantitative GHG emissions evaluation system in the case of sewage-sludge treatment systems, due to multiple emission sources, complex processes, and different standards. In previous studies, the Guidelines for National Greenhouse Gas Inventories (Intergovernmental Panel on Climate Change, IPCC, 2006) and Chinese Greenhouse Gas Inventory (National Center for Climate Change Strategy and International Cooperation, NCSC, 2005) were widely applied to estimate GHG emissions from sewage-sludge treatment. However, IPCC does not consider CO_2 emissions from sewage treatment, and NCSC does not consider CO_2 emissions from the sewage treatment and N_2O emissions from sludge treatment. Therefore, the following have been conducted in this study: (1) A GHG estimation model basing on Life Cycle Thinking (LCT) was constructed, and the research objects were CH_4, N_2O, and CO_2 that were produced by the sewage-sludge treatment system. The estimation model of CO_2 and N_2O, which were ignored in the IPCC report, were analyzed and discussed. The models of the GHG emission estimation were summarized and improved in the urban sewage-sludge treatment system under the different sewage-sludge treatment process scenarios. (2) The GHG emission load of major urban sewage-sludge treatment processes was analyzed, and the level and key links of environmental impacts generated by different processes

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were identified. This helps to understand and compare the environmental impacts of different treatment processes and provides suggestions for the sustainable development of wastewater treatment processes. (3) The GHG emission characteristics of nine scenarios of different sewage-sludge treatment processes were analyzed, and the environmental impacts caused by energy consumption and chemicals consumption were studied. Consequently, the sewage-sludge treatment process under low carbonization and low environment impact were proposed.

Keywords Greenhouse gas (GHG) emission · Mass balance · Sewage-sludge treatment system

18.1 Introduction

Climate change has become one of the most serious challenges of the twenty-first century. Until the end of 2010, the "Greenhouse Gas Bulletin" published by the World Meteorological Organization (WMO) indicated that the concentration of several major GHGs, such as methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) in the global atmosphere reached their highest level, increasing by 38%, 158%, and 19%, respectively, compared with the concentrations during pre-industrial revolution (1750 years ago) (Liu 2010). With an increase in GHG emissions, the global average temperature is predicted to increase by 5 °C in the next 100 years (World Bank, 2010). It is estimated that because of China's economic development, the atmospheric CO_2 concentration will continue to increase, leading to an increase in the average surface temperature of China by 2.2–4.2 °C in 2100 (Chen 2009). Due to rising global temperatures, governments have begun to take measures to reduce GHG emissions to meet climate change targets. In the past 100 years, the Municipal Wastewater Treatment Plants (WWTPs) have developed rapidly in order to solve environmental and health problems due to urban sewage. The traditional sewage treatment process consumes a lot of energy and medicines as well as produces GHG emissions, including CH_4, N_2O, and CO_2. In developed countries, energy consumptions, CO_2 emissions, N_2O emissions, and CH_4 emissions from WWTPs account for 3% (Mo and Zhang 2012), 4% (Martin et al. 2008), 3% (Kampschreur et al. 2009), and 5% (El Fadel et al. 2001) of total consumptions/emissions, respectively.

Meanwhile, the evaluation method of urban sewage treatment process is primarily based on technical and economic analysis to ensure the output quality of WWTPs. This evaluation method is mainly aimed at achieving water quality standards, considering the cost and benefit of different sewage treatment processes from an economic perspective, and analyzing the economic rationality of the treatment process. However, in the face of development challenges of pollutant reduction, energy conservation, and emission reduction, this emphasis on the evaluation of processing technology performance will highlight its shortcomings; thus, a systematic environmental impact analysis should be established. With the development of urbanization in China, energy consumption and GHG emissions of sewage-sludge treatment will become an important aspect of growth. As wastewater treatment is gradually moving towards sustainable development, it is necessary to systematically consider GHG emissions throughout the entire process of sewage-sludge treatment. The LCT can provide a systematic research framework for energy conservation and GHG emission reduction of sewage-sludge treatment systems.

In previous studies, the application of LCA in sewage treatment was mostly to evaluate the environmental impact (EI) of WWTPs or sewage treatment processes and to compare the sewage treatment processes. Mahgoub et al. (2010) evaluated the EI including CO_2 emissions from an urban water system in Egypt by using the LCA approach. Rodriguez RM et al. (2016) used the LCA method to compare heterogeneous and homogenous Fenton processes for the treatment of pharmaceutical wastewater. Frijins (2012) mentioned that the accounting boundary should include direct and indirect CO_2 from energy consumption, direct CH_4 and N_2O emissions from treatment processes, and indirect CO_2 emissions from production of chemicals used in relevant processes. However, little research has been conducted on the calculation of GHG emissions to account for direct CO_2 emissions from sewage treatment processes. In this study, the calculation of direct CO_2 emissions from sewage treatment was analyzed based on mass balance.

18.2 Materials and Methods

18.2.1 Boundary Definition

The sewage-sludge treatment system receives domestic sewage as well as discharge treated sewage and sludge. The sewage-sludge treatment is a complex reaction system involved a series of biological treatment. In its Second Assessment Report (1997), the IPCC considers that the carbon in BOD converts only into CH_4, whereas in the Fourth Assessment Report (2007), CO_2 generated from biomass decay is not considered a part of GHG emissions (IPCC 2007). In the case of GHG emission accounting, some studies state that electric energy consumption should be counted as a part of the energy sector rather than sewage-sludge treatment system. The influent BOD converts into CO_2 and biomass, whereas CH_4 is generated only during sludge anaerobic digestion. Direct GHG emissions are generated by the treatment of sewage and sludge. Indirect GHG emissions are generated by the consumption of chemicals and electric energy in the treatment process. The evaluation boundaries are shown in Fig. 18.1, wherein the tetragonal broken line refers to boundary of GHG emissions, tetragonal solid line refers to the treatment process, and the oval solid line refers to materials coming in/getting out the boundary.

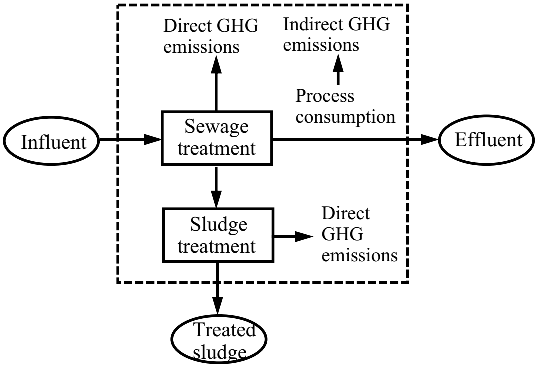

Fig. 18.1 The boundary of GHG emissions from sewage-sludge treatment system

18.2.2 Analysis of Different Sewage-Sludge Scenarios

18.2.2.1 Selection of Sewage Treatment Process

According to the List of National Urban Sewage Treatment Facilities published by the Ministry of Environmental Protection in 2014 (MEPPRC 2015), the statistical results of 4,437 operating WWTPs are shown in Table 18.1. The sewage treatment processes in descending order of quantity were Anaerobic/Anoxic/Oxic (AAO), Oxidation Ditch (OD), Sequencing Batch Reactor (SBR), and Anoxic/Oxic (AO); in descending order of sewage treatment capacity, they include AAO, OD, AO, and SBR. Therefore, three typical sewage treatment processes, namely AAO, OD, and SBR were selected. AO was eliminated as it is similar to AAO. The sum of the three analyzed processes accounted for 71.8% of the total treated water, and the average daily treated water accounted for 74.3% of the total treated water.

Table 18.1 Statistics on different sewage treatment processes of operating WWTPs (El Fadel et al. 2001)

	Number of WWTPs	Ratio *	Capacity (× 10^6 m^3/d)	Ratio **
AAO	1167	26.31%	50.50	37.35%
OD	1161	26.17%	32.65	24.15%
SBR	857	19.32%	17.32	12.81%
AO	673	15.17%	18.74	13.86%
Others	579	13.05%	16.00	11.84%
Total	4437	100.00%	135.22	100.00%

* The ratio of WWTPs using different sewage treatment processes to the total WWTPs
** The treatment capacity of WWTPs using different treatment processes accounts for the proportion of total treatment capacity of total WWTPs

18.2.2.2 Selection of Sludge Treatment Process

According to the Guideline on Best Available Technologies of Pollution Prevention and Control for Treatment and Disposal of Sludge from Municipal Wastewater Treatment Plant (MEPPRC 2010), three typical sludge treatment processes (landfill, composting, and combustion) were analyzed.

18.2.3 Sources of Estimated Input Data

This study analyzed the theoretical estimation of GHG emissions from sewage-sludge treatment scenarios in China. The estimated input data were obtained from national/industrial standards, different technical guides, and environment assessment reports. Some parameters used in this study were shown in Table 18.2.

A 40,000 m^3/day sewage treatment capacity was used to analyze different scenarios, as influent flow rates of small-scale WWTPs ($\leq$40,000 m^3/day) (MOHURD 2006) account for 81.1% of the total WWTPs (MEPPRC 2015), which is the mainstream treatment capacity of WWTPs built in China.

The effluent, which reflects the water quality of treated sewage, should be under strict control before being discharged into natural waters, such as rivers and lakes. The highest discharge standard of WWTPs in China, that is 1A-level standard (Table 18.2), was used for GHG emissions calculation.

18.3 Estimation Procedure of Ghg Emissions from Sewage-Sludge Treatment System

The sewage-sludge treatment system includes a sewage treatment process and a sludge treatment process; furthermore, GHGs can be classified into direct emissions and indirect emissions based on different emission sources. Direct emissions of GHGs include CO_2 converted by organic matter in the biotreatment process, CH_4 emitted during the anaerobic process and sludge treatment, and N_2O emitted during biological nitrogen removal. Indirect emissions of GHGs mainly include electricity consumption of mechanical equipment (such as lifting unit, aeration unit, and sludge treatment unit) and chemicals consumption (such as PAC and PAM) during treatment process.

In this study, estimation method of direct emissions of CO_2 and N_2O was based on mass balance and active sludge/anaerobic digester model (AS/AD). Indirect GHG emissions from sewage treatment and GHG emissions from sludge treatment were

Table 18.2 The assumed model parameter used in this study

Parameter	Symbol	Unit	Value uesd		
			AAO	OD	SBR
Flow rate	Q	m^3/d	40,000		
Effluent[b]	BOD_{eff}	$kgBOD/m^3$	0.01		
	COD_{eff}	$kgCOD/m^3$	0.05		
	SS_{eff}	$kgSS/m^3$	0.01		
	N_{eff}	kgN/m^3	0.015		
	P_{eff}	kgP/m^3	0.0005		
MLSS	–	kg/m^3	2.0 ~ 4.5 [a1]	2.0 ~ 4.5 [a2]	2.5 ~ 4.5 [a3]
MLVSS	–	kg/m^3	3.4 [c]	2.9 [c]	3.4 [c]
Ratio of BOD_5 and BOD_u	f_1	–	0.68 (Metcalf and Eddy 1991)		
Ratio of MLVSS and MLSS	f_2	–	0.5 ~ 0.75 [a1]	0.5 ~ 0.65 [a2]	0.75 (Fan et al. 2015)
Ratio of MLSS and SS	f_3	–	0.7 (MEPPRC 2010)		
Cell-yield coefficient	Y	kg VSS/kg BOD	0.68 (WEF and ASCE 1998)		
Endogenous decay coefficient	k_d	1/d	0.05 (WEF and ASCE 1998)		
Hydraulic retention time	HRT	day	0.46 ~ 0.75 [a1]	0.33 ~ 0.75 [a2]	0.83 ~ 1.25 [a3]
BOD removal rate	η_{BOD}	%	92.0 [d] (85 ~ 95) [a1]	97.1 [e] (85 ~ 95) [a2]	92.3 [f] (85 ~ 95) [a3]
Nitrogen removal rate	η_N	%	86.0 [d] (55 ~ 80) [a1]	78.6 [e] (55 ~ 80) [a2]	57.1 [f] (55 ~ 80) [a3]
Phosphorus removal rate	η_P	%	65.0 [d] (60 ~ 80) [a1]	93.75 [e] (50 ~ 75)[a2]	83.3[f] (50 ~ 75)[a3]
SS removal rate	η_{SS}	%	87.0[d]	97.5[e]	93.3[f]
Sludge production[g]	$X_{tre.}$	$kgDS/m^3$	0.5[d]	1.32[e]	0.2[f]
Amount of nitrogen in the biomass	$X_{N,biomass}$	kgN/kgVSS	0.122 (Hiatt and Grady 2008)		

[a1], [a2], and [a3] Technical Specifications for AAO (HJ 576–2010), OD (HJ 578–2010), and SBR (HJ 577–2010) Activated Sludge Process (Environment Protection Standards of PRC)
[b] Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant—1A level (GB18918–2002) (National Standard of PRC)
[c] calculated when the upper limit of the standard range was selected, in order to get the maximum GHG emissions
[d], [e], and [f] Environmental Impact Assessment Report of different WWTP pubulished online (websits were shown in (http://www.xuanhan.gov.cn/show/ 2019) (http://www.screnhe.gov.cn/zwgk/jbxxgk/gsgg/ 1353), and (http://www.meijiang.gov.cn/Home/NewContent?newid=83115), respectively)
[g] 60% water content

Table 18.3 The GHG emissions factor calculated in this study

Item	Emission factor	Value	Unit	References
Sewage treatment process				
N_2O	EF_{N2O}	0.253[a]	$kgN_2O/kgN_{denitrified}$	(Foley et al. 2010)
Sludge treatment process				
Landfill	$EF_{land.,ex.N2O}$	0.042	$kgCO_2e/kgDS$	(Liu et al. 2013)
	$EF_{land.,N2O}$	0.951	$kgCO_2e/kgDS$	(De 2008)
Composting	$EF_{comp.,ex.N2O}$	0.493	$kgCO_2e/kgDS$	(Liu et al. 2013)
	$EF_{comp.,N2O}$	0.656	$kgCO_2e/kgDS$	(Foley et al. 2008)
Combustion	$EF_{comb.}$	0.444	$kgCO_2e/kgDS$	(Peng et al. 2013)
Chemicals consumption				
PAM	EF_{PAM}	1.500	$kgCO_2e/kgPAM$	(Carr 2007)
PAC	EF_{PAC}	0.023	$kgCO_2e/kgPAC$	(Sharaai et al. 2012)
Energy consumption				
Electricity	$EF_{elec.}$	0.681	$kgCO_2e/kWh$	(Climate Change Division 2014)
Diesel fuel	EF_{diesel}	3.261[b]	$kgCO_2e/kg$	(IPCC 2007) (NBSC 2016)

[a] In order to get the maximum GHG emissions, the upper limit is selected
[b] calculated when diesel fuel density is 0.84 kg/L

estimated by GHG emission factor method, and the emission factors used are shown in Table 18.3.

18.3.1 Estimation of CO_2 Direct Emissions from Sewage Treatment Process

18.3.1.1 CO_2 Emissions from Aerobic Oxidation of Organic Matter

In the biotreatment process, organic matter is oxidized by microorganisms (biomass) under aerobic conditions to produce CO_2. In this study, the organic matter is represented by $C_{10}H_{19}O_3N$ (Rittmann 2001), and the oxidation process of $C_{10}H_{19}O_3N$ is described as follows:

$$2\ C_{10}H_{19}O_3N + 25\ O_2 \rightarrow 20\ CO_2 + 16\ H_2O + 2\ NH_3$$

A conversion factor was 1.1 kg CO_2 for every 1 kg O_2 produced is obtained. Thus, CO_2 emissions from aerobic oxidation of organic matter can be obtained from Eq. (18.1):

$$E_{CO2,ae} = 1.1 \times \frac{\eta_{BOD}}{1 - \eta_{BOD}} \times BOD_{eff} \times Q \times \left(\frac{1}{f_1} - 1.42\,Y\right) \tag{18.1}$$

18.3.1.2 CO_2 Emissions from Biomass Endogenous Decay

Biomass is represented by $C_5H_7O_2N$ (Rittmann 2001), and the chemical reaction of biomass endogenous decay is described, as follows:

$$C_5H_7O_2N + 5O_2 \rightarrow 5CO_2 + 2H_2O + NH_3$$

A conversion factor of 1.947 kg of CO_2 for every 1 kg of biomass decayed endogenously was obtained. The CO_2 emissions arising from endogenous decay can be estimated from Eq. (18.2).

$$E_{CO2,de} = 1.947 \times Q \times HRT \times MLVSS \times k_d \tag{18.2}$$

18.3.1.3 CO_2 Emissions from Nitrogen Removal

Biological nitrogen removal process includes nitrification and denitrification. These two processes can be described respectively, as follows:

$20\ CO_2 + 14\ NH_4^+ \rightarrow 10\ NO_3^- + 4\ C_5H_7O_2N + 24\ H^+ + 2\ H_2O$

$C_{10}H_{19}O_3N + 0.5\ HCO_3^- + 0.5\ NH_4^+ + 4.8\ NO_3^- + 4.8\ H^+ \rightarrow 26\ C_5H_7O_2N + 40\ CO_2 + 2.4\ N_2 + 7.9\ H_2O$

CO_2 is fixed during the nitrification process. However, the CO_2 produced during denitrification is not calculated because the CO_2 produced is already included in the calculation for $C_{10}H_{19}O_3N$ oxidation.

A conversion factor of 4.49 kg CO_2 every 1 kg oxidized nitrogen is obtained. The CO_2 emissions arising from nitrification can be estimated from Eq. (18.3):

$$E_{CO2,N} = 4.49\left(\frac{\eta_N}{1 - \eta_N} \times N_{eff} \times Q - X_{N,biomass}\right) \tag{18.3}$$

Thus, the estimation of CO_2 generation from sewage treatment process can be described by Eq. (18.4).

$$E_{CO2,sewage} = E_{CO2,ae} + E_{CO2,de} - E_{CO2,N} \tag{18.4}$$

18.3.2 Estimation of N_2O Direct Emissions from Sewage Treatment Process

The global warming potentials (GWPs) (over 100 years) of CH_4 and N_2O are 25 times and 298 times that of CO_2, respectively (IPCC AR4 2007) (IPCC 2007). The emissions of CH_4 and N_2O were converted into carbon dioxide equivalents (CO_2e) by GWP to estimate GHG emissions in this study.

The N_2O emission during the sewage treatment occurred in the biological nitrogen removal process that mainly consisted of nitrification process and denitrification process. (Kampschreur et al. 2009) This study found that N_2O was not only generated as an intermediate product in the denitrification process but was also generated as a by-product in the nitrification process (He et al. 2001). The mechanism of N_2O production as an intermediate product and by-product is complicated, as it is affected by enzyme inactivation, accumulation of NO_2^-, and reaction condition (such as pH, DO, and C/N) (Marlies et al. 2009). The N_2O emission from sewage treatment was calculated, as shown in Eq. (18.5).

$$E_{N2O,sewage} = Q \times \Delta N \times EF_{N2O} \times GWP_{N2O} \tag{18.5}$$

18.3.3 Estimation of GHGs Indirect Emissions from Sewage Treatment Process

The indirect emission of GHGs mainly include electrical energy consumption of mechanical equipment (such as lifting unit, aeration unit, and sludge treatment unit), and chemicals consumption (such as polyaluminum chloride (PAC) and polymers (PAM)) during treatment process. The consumptions are shown in Tables 18.3 and 18.4. The GHGs indirect emissions from sewage treatment was calculated, as shown in Eq. (18.6).

$$E_{indirect,\ sewage} = \sum EF_i C_i Q \tag{18.6}$$

Thus, GHGs emissions from sewage treatment was calculated, as shown in Eq. (18.7).

$$E_{GHG,\ sewage} = E_{CO_2,\ sewage} + E_{N_2O,\ sewage} + E_{indirect,\ sewage} \tag{18.7}$$

Table 18.4 Electric and chemicals consumptions (C_i)

Treatment process		PAC ($kgPAC/m^3$)	PAM ($kgPAM/m^3$)	Electric (kWh/m^3)/(kWh/t)	Diesel (kg/t)
Sewage	AAO[a1]	1.507E-05	2.740E-04	1.479	–
	OD[a2]	1.644E-02	6.575E-03	2.959	–
	SBR[a3]	–	6.425E-04	–	–
Sludge (Liu et al. 2013)	Land.	–	–	–	4.2
	Comp.	–	–	28.8	0.22
	Comb.	–	–	14	24.6

[a1],[a2], and[a3] Environmental Impact Assessment Report of different WWTP pubulished online (websits were shown in (http://www.xuanhan.gov.cn/show/ 2019) (http://www.screnhe.gov.cn/zwgk/jbxxgk/gsgg/ 1353), and (http://www.meijiang.gov.cn/Home/NewContent?newid=83115), respectively)

18.3.4 Estimation of GHG Emissions from Sludge Treatment Process

In this study, three types of sludge treatment processes (landfill, composting, and combustion) were considered, because these are the main sludge treatment process. According to the current statistics on all sludge treatment methods, landfill accounts for 60–65%, land use after composting accounts for 10–15%, comprehensive utilization after natural drying accounts for 4–6%, and combustion accounts for 2–3% (Dai 2011). The emission factor method was used to estimate GHG emissions of three sludge treatment processes. The emission factors of different sludge treatments were shown in Table 18.3.

18.3.4.1 Landfill (Anaerobic Digestion)

The main reaction in the sludge landfill process is anaerobic digestion, where the organic matter slowly releases CH_4 under anaerobic conditions. Although N_2O emissions are usually small, they still need to be considered because the GWP of N_2O is relatively high. The GHG emissions from sludge landfill (anaerobic digestion) are described by Eq. (18.8).

$$E_{GHG,\ land.} = \left(EF_{ex.N_2O,\ land.} + EF_{N_2O,\ land.} + \sum EF_i C_i\right) \times X_{tre.} \times Q \qquad (18.8)$$

18.3.4.2 Composting (Aerobic Digestion)

The main reaction in the sludge composting process is aerobic digestion, where the organic matter, which is oxidized, releases CO_2 under aerobic conditions. N_2O emissions were also considered in this study. The GHG emissions from sludge composting (aerobic digestion) were described by Eq. (18.9).

$$E_{GHG,\,comp.} = \left(EF_{ex.N_2O,\,comp.} + EF_{N_2O,\,comp.} + \sum EF_iC_i\right) \times X_{tre.} \times Q \qquad (18.9)$$

18.3.4.3 Combustion

The organic matter was completely oxidation into CO_2. Peng J. et al. (Fan et al. 2015) analyzed the GHG (CO_2 and N_2O) emissions from the sludge combustion process and obtained a conversion value of 0.444 kg CO_2e per kg of sludge. The GHG emissions from sludge combustion are described using Eq. (18.10).

$$E_{GHG,\,comb.} = \left(EF_{comb.} + \sum EF_iC_i\right) \times X_{tre.} \times Q \qquad (18.10)$$

where,

$E_{CO2,ae/de}$	CO_2 emissions rate from organic matter oxidation/endogenous decay, kgCO_2e/d;
$E_{CO2,N}$	CO_2 fixation rate from nitrification, kgCO_2e/d;
$E_{CO2/N2O,sewage}$	CO_2/N_2O emission rate from sewage treatment, kgCO_2e/d;
$E_{indirect,sewage}$	Indirrect GHG emissions from sewage treatment, kgCO_2e/d;
$E_{GHG,sewage}$	GHG emissions from sewage treatment, kgCO_2e/d;
$E_{GHG,land.}$ ($E_{GHG,comp.}$/$E_{GHG,comb.}$)	GHGs emission rate from sludge landfill (composting/combustion) treatment process, kgCO_2e/d;
i	The different consumables used in treatment process;
EF_i	GHG emission factors of different consumables; and
C_i	Consumptions of different consumables

18.4 Results and Discussions

18.4.1 GHG Emissions of Different Sewage-Sludge Treatment Scenarios

GHG emissions from different sources for the nine sewage-sludge treatment scenarios (S1–S9) are shown in Table 18.5.

The GHG emission ranges (with different sludge scenarios) of SBR, AAO, and OD are 58–60 ktCO_2e/a, 122–127 ktCO_2e/a, and 113–125 ktCO_2e/a, respectively. The direct GHG emissions of SBR (33.87 ktCO_2e/a) are much less than AAO (109.78 ktCO_2e/a) and OD (89.86 ktCO_2e/a), while the indirect GHG emissions are similar, namely 24.86 ktCO_2e/a (SBR), 14.94 ktCO_2e/a (AAO), and 30.18 ktCO_2e/a (OD). The ratio of direct to total GHG emissions were calculated to be 88% (AAO), 75% (OD), and 58% (SBR). The contribution of GHG emissions from wastewater treatment accounted for many of the total emissions, which were 94.8% for AAO, 85.8% for OD, and 95.6% for SBR.

In the nine sewage-sludge treatment scenarios, SBR-Combustion (S9) scenario had the least amount of GHG emissions, while the AAO-Composting (S2) scenario had the most GHG emissions. The total GHG emissions, in descending order, were S2, S1, S5, S4, S3, S6, S8, S7, and S9. The total emissions of SBR scenario were less than AAO and OD, even under different sludge treatment scenarios.

The ratio of GHG emissions from sludge treatment and total emissions were approximately 5.2% (AAO), 14.2% (OD), and 4.4% (SBR). GHG emissions from different sludge treatment scenarios (same sewage treatment), in descending order, are composting, landfill, and combustion. The reduction rate of GHG emissions under combustion scenario, when compared to landfill were 2.8% for AAO, 7.6% for OD, and 2.4% for SBR; when compared to composting were 3.6% for AAO, 9.6% for OD, and 3.1% for SBR. Therefore, the effect of sludge treatment process selection in reducing GHG emissions is positive, without changing the sewage treatment process.

18.4.2 GHG Emissions from Different Sources

The GHG emissions of sewage-sludge treatment system were divided into six emission sources among nine different scenarios. The six emission sources were CO_2 from sewage treatment, N_2O from sewage treatment, chemicals consumption from sewage treatment, electricity consumption from sewage treatment, direct GHG emissions from sludge treatment, and indirect GHG emissions from sludge treatment, as shown in Fig. 18.2.

The contribution of each emission source (in descending order) in the AAO scenario were 80.12-83.12% (N_2O), 11.62–12.05% (electricity), 2.66–5.77% (direct emission from sewage treatment), 1.62–1.67% (CO_2), 0.004–0.49% (indirect emission from sewage treatment), and less than 0.005% (chemicals).

Table 18.5 GHG emissions from different sources for the nine sewage-sludge treatment scenarios (kgCO_2e/d)

			Total	Sewage treatment				Sludge treatment	
				Direct GHG emissions		Indirect GHG emissions		Direct GHG emissions	Indirect GHG emissions
				CO2	N2O	Chemicals	Electricity		
AAO	landfill	S1	3.44E+05	5.64E+03	2.78E+05	1.65E+01	4.03E+04	1.99E+04	2.74E+02
	comp.	S2	3.47E+05	5.64E+03	2.78E+05	1.65E+01	4.03E+04	2.30E+04	1.43E+01
	comb.	S3	3.34E+05	5.64E+03	2.78E+05	1.65E+01	4.03E+04	8.88E+03	1.62E+03
OD	landfill	S4	3.35E+05	3.45E+04	1.66E+05	4.10E+02	8.06E+04	5.24E+04	7.23E+02
	comp.	S5	3.42E+05	3.45E+04	1.66E+05	4.10E+02	8.06E+04	6.07E+04	3.79E+01
	comb.	S6	3.09E+05	3.45E+04	1.66E+05	4.10E+02	8.06E+04	2.34E+04	4.29E+03
SBR	landfill	S7	1.62E+05	2.57E+04	6.02E+04	3.86E+01	6.78E+04	7.94E+03	1.10E+02
	comp.	S8	1.63E+05	2.57E+04	6.02E+04	3.86E+01	6.78E+04	9.19E+03	5.74E+00
	comb.	S9	1.58E+05	2.57E+04	6.02E+04	3.86E+01	6.78E+04	3.55E+03	6.49E+02

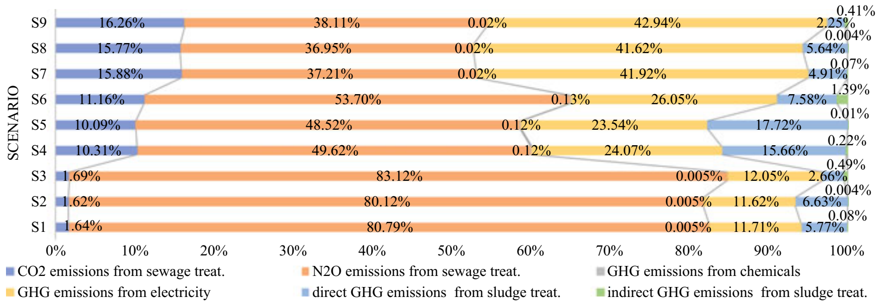

Fig. 18.2 Percentage of the GHG emission sources under different sewage-sludge treatment scenarios

The contribution of emission source (in descending order) in the OD scenario were 48.52–49.62% (N_2O), 23.54–24.07% (electricity), 15.66–17.72% (direct emission from sewage treatment), 10.09–10.31% (CO_2), 0.01–0.22% (indirect emission from sewage treatment), and 0.12% (chemicals). S6 scenario showed a different result (OD-combustion): the contribution of CO_2 (11.16%) is more than direct GHG emissions from sludge treatment (7.58%), and the contribution of indirect GHG emissions from sludge treatment increased to 1.39%.

The contribution of each emission source in the SBR scenario, in descending order, was 41.62–42.94% (electricity), 36.95–38.11% (N_2O), 15.26–16.26% (CO_2), 2.25–5.64% (direct emission from sewage treatment), 0.01–0.41% (indirect emission from sewage treatment), and 0.02% (chemicals).

18.4.3 CO_2 Emissions from Sewage Treatment and N_2O from Sludge Treatment

The IPCC does not consider the CO_2 emissions from sewage treatment, and NCSC does not consider the CO_2 emissions from the sewage treatment and the N_2O emissions from sludge treatment.

As described in Fig. 18.2, the contribution ranges of GHG emissions from CO_2 were 1.62–1.69% for AAO, 10.09–11.16% for OD, and 15.77–16.26% for SBR. Therefore, it is necessary to estimate CO_2 emissions from wastewater treatment when estimating GHG emissions, at least in OD and SBR systems.

The direct GHG emissions from sludge treatment account for 2.66–6.62% (AAO), 7.58–17.72% (OD), and 2.25–5.64% (SBR) of total wastewater sludge treatment systems. Moreover, it accounts for more than 95% of the GHG emissions from the sludge system.

18.5 Summary

In this study, nine scenarios of different sewage-sludge treatment processes were analyzed to estimate the GHG emissions. According to national statistics, the limiting design values of mainstream WWTPs were defined as the limit values in the scenario study. The sewage flow rate was assumed to be 40,000 m^3/d, and the 1-A standard was assumed as effluent limit. Results shown that three sources, direct emissions of CO_2 and N_2O, and indirect emissions of electricity consumption are significant contributors to the GHG emissions of sewage-sludge systems. The total GHG emission ranged from 58-127 ktCO_2e per year, with the lowest GHG emissions obtained from the SBR-Combustion scenario and the largest GHG emissions obtained from the AAO-Composting scenario.

N_2O emissions and electricity consumption are the primary sources of GHG emissions, and the sum of the contributions of these two sources exceeds 70% in all scenarios. CO_2 emissions have not been considered in GHG emissions estimation of IPCC, as it is of the biogenic origin. This study highlights that not considering CO_2 emissions in the results of GHG emissions estimation may cause deviations in the results.

According to China's statistics, total GHG emissions from the wastewater treatment industry in 2005 was 114 million tons of CO_2 equivalent (National Development and Reform Commission for responding to climate change 2013), and the ratio of three processes (AAO, OD, and SBR) treatment capacity and the total processing capacity were 37%, 24%, and 13%, respectively (MEPPRC 2015). The result of this study revealed that the contribution of direct CO_2 emissions to GHG emissions in three processes were 1.65%, 10.52%, and 15.97%, respectively. Therefore, it can be inferred that in the scenario of calculating direct CO_2 emissions from the sewage treatment when calculating GHG emissions, total GHG emissions from the wastewater treatment industry in 2005 should be 150 million tons of CO_2 equivalent, an increase of approximately 32% compared to the statistics in 2005.

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Part IV
Sustainability Education

Chapter 19
Gamifying Sustainable Design to Enhance Environmental Consciousness of Industrial Design Students

Suphichaya Suppipat, Allen H. Hu, and Treechada Chotiratanapinun

Abstract Gamification is the use of game elements, mechanics, and experience design to engage user behaviors and solve real-world problems. Applications of serious games and gamification in sustainable design education have been novel. To raise environmental consciousness and knowledge of industrial design students, the gamification design system was integrated into sustainable design pedagogy. The aim is to evaluate the learning effectiveness of this intervention. The study was conducted in a sustainable design course for three consecutive years at the Department of Industrial Design, Chulalongkorn University, Thailand. Nine Eco-Game projects were designed and playtested. Participant observations and evaluations by checklists and web-based questionnaires were then performed during in-classroom activities among sophomores and juniors. Results revealed that the integration can enhance learning outcomes in environmental information and design aspects depending on the complexity of game rules, adequacy of prototype testing period, and concentration for physical actions and game tasks. In this way, students can learn through playing and designing games. However, this phase is solely at the early stage of intervention in this field. Further research is needed to fully integrate systematic gamification into the learning environment and encourage pro-environmental behavior change.

Keywords Sustainable design · Gamification · Life cycle design · Environmental consciousness · Industrial design students

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19.1 Introduction

Over the past decades, taking into account environmental issues during new product development has become a major challenge for industrial designers. Given the importance of a design decision in environmental impacts, sustainable design is defined as the integration of social, environmental, and economic design aspects that can critically change production and consumption patterns. The three main principles of sustainable design are socially responsible design, life cycle design, and resource-based economy (Deniz 2016). When considering sustainable design education, one of the relevant problems among industrial designers is lack of knowledge and information on environmental performance, which stems from limited sustainability awareness during design and planning stages (Deniz 2016; Lofthouse 2006). The application of sustainable design principles can extend the awareness of environmental issues in every scale of design education, and it requires a new way of thinking and certain frameworks for consideration (Deniz 2016). Recently, various gamified interventions have been implemented in many contexts, including design education (Herrington and Reeves 2011; Landers et al. 2018; Oberprieler et al. 2017; Boks and McAloone 2009). Gamification is the use of game design elements and mechanics in non-game contexts to engage users and affect real-world experiences (Landers et al. 2018; Oberprieler et al. 2017; Wiggins and Khosrow-Pour 2018). Thus far, gamification has been a novel concept introduced in a sustainable design curriculum. Integrating sustainable design pedagogy with gamification techniques is of interest to raise environmental consciousness of students and expand learning outcomes. The aim of this research project is to evaluate and validate the effectiveness of integrating gamification with sustainable design practices in higher education. This study was conducted annually for three consecutive years as part of the sustainable design course at the Department of Industrial Design, Chulalongkorn University in Bangkok, Thailand and implemented through a design assignment called "Eco-Game Project."

19.2 Background

19.2.1 Gamification in Design Education

Gamification and serious games have been recently developed to educate and motivate users in several fields. Boks and McAloone also suggested that gamifying should be aimed at educating a selected audience (Boks and McAloone 2009). The academia has put forward various definitions of gamification (Herrington and Reeves 2011; Landers et al. 2018; Oberprieler et al. 2017, 2018). Oberprieler et al. (2017) offered one of the most inspiring definitions, that is gamification is the use of game mechanics and the design of experiences to engage users and solve problems in the real world. Gamification differs from games and game-based learning in important ways. A game is defined as a physical activity that often uses objects and prompts player interaction (Oberprieler et al. 2017), whereas game-based learning is described as the use of games to support learning as well as gathering knowledge and skills (Oberprieler et al. 2017; Wiggins and Khosrow-Pour 2018). Despite its distinct interpretation, the application of gamification is intended to change human behavior (Landers et al. 2018; Oberprieler et al. 2017; Morganti et al. 2017) and, in particular, to develop games for serious purpose (Morganti et al. 2017). Considering recent developments on design educational landscape, gamification offers an innovative approach to produce improved learning outcomes and student collaboration and enable design educators to expand design curriculum and create innovative teaching methods (Oberprieler et al. 2017; Boks and McAloone 2009).

Oberprieler et al. (2017) enumerated the four orders of gamification, which are playful design, basic gamification, interactive gamification, and systematic gamification. Elevating from the first to the fourth order is based on three aspects, namely, complexity of the learning behavior being gamified, duration of gameplay, and integration of the gamified and real worlds. The four criteria for each order comprise objective, rules, reward, and integration (Fig. 19.1).

The gamification design system is divided into five-phased approaches, which are intent, explore, make-test-learn, launch, and evolve (Oberprieler et al. 2017) (Fig. 19.2). Oberprieler et al. (2017) also suggested that design educators can use this system as a framework to extend design curriculum. The curriculum should be constructed using mechanics and dynamics based on the order to gamify the learning extent.

Recently, advancements in design education have renewed interest in introducing gamification in design curriculum and pedagogical practice to develop soft skills, transversal competencies, collaborative production, and system thinking (Herrington

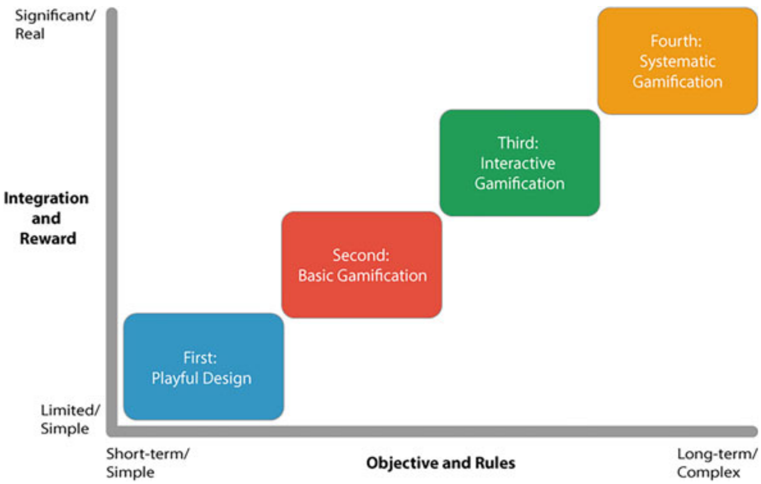

Fig. 19.1 Four orders of gamification (adapted from Oberprieler et al. (2017))

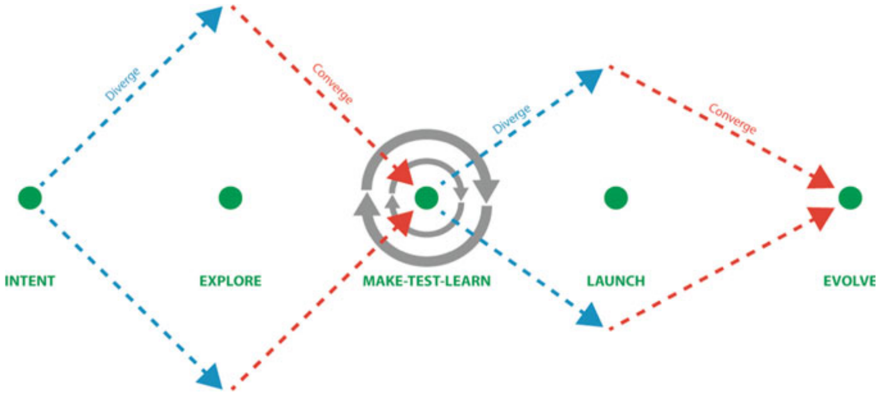

Fig. 19.2 Gamification design system (adapted from Oberprieler et al. (2017))

and Reeves 2011; Oberprieler et al. 2017; Whalen et al. 2018). Applied gaming (serious games and gamification) interventions have already been used in environmental (Morganti et al. 2017) and circular economy education (Whalen et al. 2018). Moreover, most games used in sustainable product design education describe games as a method of teaching but not the game design itself (Boks and McAloone 2009). However, the discussion is limited to the integration of gamification design system into sustainable design pedagogy, especially to raise environmental awareness and provide life cycle design thinking.

19.2.2 Sustainable Design Principles and Tools

The three main principles of sustainable design include socially responsible design, life cycle design, and resource-based economy (Deniz 2016). As Behrendt et al. explained, “Life cycle design is the design of products and processes that encompasses the entire life cycle of a product: from raw material extraction and processing to the production, distribution, use and return of materials to the industrial cycle or their disposal” (Behrendt et al. 2012). The most important tasks include assessment and reduction of the environmental impacts of a product throughout its entire life cycle as well as maintenance of its functional performance and improvement of its environmental quality (Behrendt et al. 2012; Umeda et al. 2009; Tao and Yu 2018; Plaschke et al. 2019). To cover a wide range of approaches in sustainable design education, various concepts and tools related to eco-efficiency, eco-effectiveness, and life cycle and system thinking have been introduced (Deniz 2016; Lofthouse 2006,2017; Suppipat 2016,2018). The intention is to motivate students to advance from product improvement toward system innovation, in which considerable environmental and social improvement, as well as economic benefits, can be executed (Boks

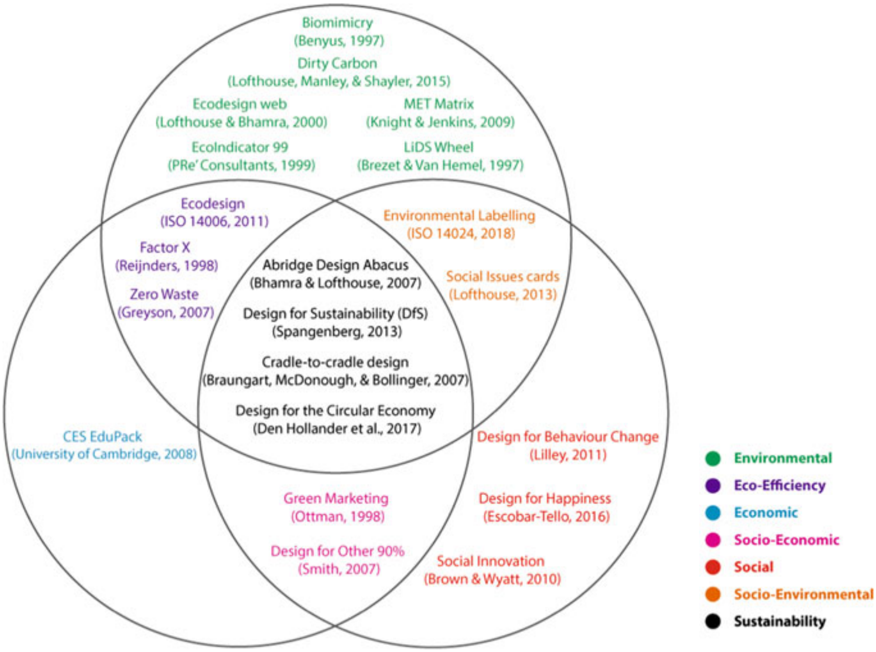

Fig. 19.3 Concepts and tools of sustainable design principles (data sourced from (Lofthouse 2017; Benyus 1997; Knight and Jenkins 2009; Pré Consultants 2000; Brezet and Hemel 1997; ISO 14006 2011; ISO 14024 2018; Greyson 2007; Spangenberg 2013; Hollander et al. 2017; Ashby 2008; Reijnders 1998; Ottman and Business Books 1998; Smith 2007; Bhamra et al. 2011, 2016; Brown and Wyatt 2010; Braungart et al. 2007))

and McAloone 2009; Lofthouse 2017; Brezet and Hemel 1997). The various concepts and tools used currently in sustainable design pedagogy are shown in Fig. 19.3.

When considering sustainable design education, one of the major problems among industrial design students is lack of knowledge and information on environmental performances, such as materials and construction techniques, design processes, as well as possible solutions (Deniz 2016; Lofthouse 2006). Many existing tools aim at strategic management or retrospective analysis of products, not on prospective design issues (Lofthouse 2006; Walker 1998). Furthermore, environmental system analysis tools, such as life cycle assessment (LCA), require background knowledge on natural science and mathematics, which tends to be difficult for design students to comprehend and apply correctly in the shortest possible time (Lofthouse 2006; Suppipat 2016). The findings from the pilot study of eco-design tool application by Lofthouse (Lofthouse 2006) show that many designers prefer a non-technical approach and ask for brief information that can be easily deduced. Moreover, designers are searching for tools that combine sustainable design guidance, information, and education (Lofthouse 2006). The content should be grounded in specific design information, materials, and construction techniques, as well as current design data sources and case studies. The designers' comments reveal that displaying information by using images is more useful, interesting, and stimulating than displaying in a written format (Lofthouse 2006). Thus, using game design elements and mechanics can potentially be an alternative for data visualization. To engage and provide design students with sustainable design skills, knowledge, and experiences, design educators can integrate gamification techniques, which can foster collaboration and embed sustainable design practices into the learning experience.

19.3 Materials and Methods

This section describes the teaching context, data collection, and evaluation of the learning outcomes cultivated in this research project. The study was implemented at the Department of Industrial Design, Chulalongkorn University (IDCU) and was conducted among bachelor-level industrial design students. IDCU is the second department in the Faculty of Architecture located in Bangkok, Thailand where sustainable design is an elective course for sophomores and juniors.

19.3.1 Participants

All participants were second- and third-year industrial design students who registered for the sustainable design course during consecutive years in 2016 ($n = 10$), 2017 ($n = 7$), and 2018 ($n = 8$). The students were assigned to design and play the "Eco-Game Project" in this course. First, basic knowledge about life cycle design, such as the characterization factors (CFs) in life cycle impact assessment (LCIA), definitions of a functional unit and LCA, and LCA tools, including Lifecycle Design Strategies (LiDS) wheel (Brezet and Hemel 1997), Materials, Energy use and Toxic emissions (MET) matrix (Knight and Jenkins 2009), and Eco-indicator 99 (Pré Consultants 2000), was introduced during the first three weeks of the course. Afterward, students were divided into groups of three and were tasked to design a serious game. They were allowed to choose their content, target players, and difficulty level for creating an hour-long serious game for two to four players that can raise their environmental awareness. The gamification design system was implemented during this four-week design project. Within this period, the proposed design concepts and game elements of each group were reviewed and received feedback every other week from at least one of the authors. Finally, the final prototypes of each group were developed and played by all as an in-classroom activity. Each game testing session was facilitated by at least one of the group members. This group member introduced the players to the game and rules, stayed during the game to answer questions, and played along. Upon completion of all game testing sessions, all participants were requested to answer the questionnaire and write a reflection on the condition of anonymity.

19.3.2 Data Collection

This study comprised five main data collection phases, namely, intent, explore, make-test-learn, launch, and evolve. Phase 1, an intent to raise environmental awareness, was a preliminary discussion between instructors and students on potential issues of interest. An unstructured interview was adopted in this phase. Phase 2, an exploration of life cycle design, clarified the target players and learning outcomes of the Eco-Game Project. Students reviewed related literature and collected primary data as a group. Phase 3, make-test-learn, used game design elements and mechanics to create a physical, serious game by making a paper prototype. Prototype testing and developing were preceded as cyclical processes to accomplish a final playable prototype. Phase 4, the launch of the game, included preparing all participants for the introduction of each game, rules, and objectives. A sustainable design checklist was used to indicate which game could contribute all three main aspects of sustainable design. Phase 5, an evolution of the game, was related to monitoring and evaluating a gamification solution for effective learning outcomes and environmental consciousness enhancement. A participant observation approach was chosen to collect qualitative data during the in-classroom activity and all phases.

19.3.3 Evaluation

To evaluate the learning outcomes of the integrated gamification with sustainable design in this study, two different tools were applied, namely, a checklist for an instructor and a web-based questionnaire for students. Sustainable design principles and gamification order checklists were used to indicate simply if the three main principles are "present" or "not present" in the content of each game, as well as which gamification order is applied through the game development. The web-based questionnaire was designed based on a rating scale and an open-end question. Six questions rating students' pre- and post-knowledge of environmental issues, attitudes to game content and elements, and feelings while playing each game, were constructed with a Likert-type scale. This type of scale is one of the most practical methods to quantitatively examine quality, and a five-point scale was used in this study, ranging from poor to excellent (1 = Poor, 2 = Fair, 3 = Average, 4 = Good, and 5 = Excellent). The median and mode of each question were determined to compare the measures of central tendency in three different years of this intervention. In a short reflective essay format, two open-end questions asked for students' opinion on the most favorite elements and further suggestions for each game. Using this format allowed the authors to identify a common theme from the content of the reflective essays.

(a) (b) (c)

Fig. 19.4 Eco-Game Projects in 2016. **a** Save the Polar! by Naphatsorn Sirivattanavit, Nathaporn Anunswat, and Nicha Rodphothong. **b** Drop 'n' Go by Jutharat Charoenchaichana, Natnicha On-mang, Pimwipha Cheaptumrong, and Yada Wongrasmidien. **c** Integro by Pakorn Turapan, Parishchaya Pramniya, and Parke Namchaisiri

(a) (b) (c)

Fig. 19.5 Eco-Game Projects in 2017. **a** 7 Disasters by Pornchai Pankumyard and Prangmas Anugul. **b** SusSeat by Jitapa Thaveehan, Kittapart Salapornchai, and Yanothai Treeratchoti; **c** Waste Survival by Athicha Supasaringkarn and Thanyamon Silamom

(a) (b) (c)

Fig. 19.6 Eco-Game Projects in 2018. **a** Circular Factory by Chadaporn Apichokcharoenchai, Ittichote Chanchaiworavit, and Napasawan Pradupkarn. **b** Magic Village by Pitapa Radjaipid, Jinjuta Pratheeptinthong, and Rywin Suntharindhu. **c** Trash Eater by Vanitsata Ngernyoo and Yommana Mahabandhu

19.4 Results and Discussion

Nine Eco-Game projects were designed and playtested (Figs. 19.4, 19.5, 19.6). The game content included various topics, such as climate change, waste sorting, greenhouse gas (GHG) emissions, LCA, upcycling, and cleaner production (Table 19.1). Four out of nine games focused on waste identification and sorting, which tended to be the most thought-provoking issue. SusSeat, which was designed in 2017 presented its game content by combining knowledge of LCA and material selection as design guidance for designers. This game used Eco-indicator 99 database, brand analysis, as well as furniture design and manufacturing techniques as pathway of the game.

Integro and Circular Factory, which are strategic planning games, showed the effectiveness of integrating gamification to cover all three principles of sustainable design within game contents. The other games could tackle mostly two of the principles. Designed in 2016, Integro presented the levels of GHG emissions from different sectors and each player, as a world leader, was tasked to manage and set the policy to reduce emissions. Circular Factory was designed in 2018 and presented the role of plastic manufacturers in managing their raw material procurement, production line, and resource recovery.

Referring to the checklist results, considerable differences were observed among the four orders of gamification achieved by the projects (Table 19.1). Two groups of students can achieve the third order of gamification, (i.e. interactive gamification), by interconnecting with real-life benefits on strategic planning and including collaboration with other players during playing games. This stage encourages social interactions and stimulates knowledge creation. Most of the games can accomplish the second order of gamification, (i.e. basic gamification), by applying game elements and mechanics to incentivize and reward simple real-world behaviors, such as helping how to sort waste in everyday life, what materials can be recycled, and how to select materials for eco-product design. Only two games focused mainly on entertaining players and provided general knowledge about climate change. The students can apply game-like mechanics to attract players' attention, as well as engage and enjoy the game for a brief period. However, none of them can elevate their games toward systemic gamification yet.

The measures of central tendency during consecutive years from 2016 to 2018 were provided in Tables 19.2, 19.3, and 19.4, respectively. The results showed that the students gained additional knowledge after playing only five of the games, namely, Save the Polar!, Drop 'n' Go, Integro, Circular Factory, and Magic Village. The short reflective essays in Table 19.5 present various factors, including complexity of rules, inadequate prototype testing in phase 3, and ignorance of knowledge due to physical actions and focusing on tasks, considering the poor response from gaining new knowledge. This issue was similarly reported by Oberprieler et al. (2017), whereby the players only focused on achievement instead of transformation of learning.

Landers et al. (2018) stated that "Gamified applications may not even be intended to be fun." However, questionnaire results showed that having fun is correlated with students' satisfaction toward learning experiences. Student's reflective essays

Table 19.1 Sustainable design principles and gamification order checklists

			Principles of sustainable design			Gamification orders			
Year	Game title	Content	Life cycle design	Resource-based economy	Socially responsible design	First: Playful design	Second: Basic gamification	Third: Interactive gamification	Fourth: Systematic gamification
	Save the Polar!	Climate change		✓		✓			
2016	Drop 'n' Go	Waste sorting		✓	✓		✓		
	Integro	GHG emissions	✓	✓	✓			✓	
	7 Disasters	Climate change		✓		✓			
2017	SusSeat	LCA and Cleaner production	✓	✓			✓		
	Waste Survival	Waste sorting		✓	✓		✓		
2018	Circular Factory	Upcycling and Cleaner production	✓	✓	✓			✓	
	Magic Village	Waste sorting		✓	✓		✓		
	Trash Eater	Waste sorting		✓	✓		✓		

Table 19.2 Measure of central tendency in 2016

Year	2016 ($n = 10$)					
Game title	Save the Polar!		Drop 'n' Go		Integro	
Questions	Median	Mode	Median	Mode	Median	Mode
1. My knowledge of environmental issues before playing game is …	3	3	3	3	3	3
2. My knowledge of environmental issues after playing game is…	4	4	4	4	4	4
3. The game instruction is straightforward	4	4	4	4	3.5	4
4. This game is interesting	4	4	4	3 and 4	4	4
5. This game is fun	4	4	4	4	4	4
6. My learning experience satisfaction is…	4	4 and 5	4	4	4	4

Table 19.3 Measure of central tendency in 2017

Year	2017 ($n = 7$)					
Game title	7 Disasters		SusSeat		Waste Survival	
Questions	Median	Mode	Median	Mode	Median	Mode
1. My knowledge of environmental issues before playing game is …	3	3	3	3	4	3 and 5
2. My knowledge of environmental issues after playing game is…	3	3	3	3	3	3
3. The game instruction is straightforward	3	3	4	4	2	4
4. This game is interesting	4	4	5	5	3	3
5. This game is fun	4	4 and 5	4	4	3	3
6. My learning experience satisfaction is…	4	4	4	4	3	3

Table 19.4 Measure of central tendency in 2018

Year	2018 ($n = 8$)					
Game title	Circular Factory		Magic Village		Trash Eater	
Questions	Median	Mode	Median	Mode	Median	Mode
1. My knowledge of environmental issues before playing game is …	3	3	3	3	3	3
2. My knowledge of environmental issues after playing game is…	4	4	4	4	3	3
3. The game instruction is straightforward	3	3	4	3 and 5	4	4
4. This game is interesting	4	4	3.5	4	4	4
5. This game is fun	3	3	4.5	5	4.5	4 and 5
6. My learning experience satisfaction is…	3	3	4	4	4	4

expressed that their most favorite game elements included physical actions, application of graphics and design elements (either 2D or 3D), interactions with other players and teamwork, game flow and storytelling, and role-playing that corresponded to a real-world situation. Other new knowledge gains from playing those games were reported by participants, such as specific design information, materials, and production techniques, as well as product design case studies. These items were parallel with the results of Lofthouse's (2006) pilot test on designer requirements of the ecodesign tools.

For further suggestions, students reflected that learning by playing and designing games can broaden their knowledge and unlearn environmental myths. Readability, interface design, and data visualization by applying suitable images and colors are greatly important in game design. Moreover, providing additional information about design solution and environmental problem prevention can be useful for learning experiences. Finally, games that can interconnect with a real-world situation, especially with cost-conscious and marketing information, are beneficial.

Evaluating the learning effectiveness of this intervention is difficult due to the small number of participants and insufficient evidence of a previous study setting without the game assignment. Further research is required by applying pre- and

Table 19.5 Student reflective essays

Year	Game title	Student reflections	
		Most favorite elements	Further suggestions
2016	Save the Polar!	– Consequence cards and the actions in the game are related to real-life behavior and/or situations – Simple playing methods and rules – Interactions with other players by teasing and swapping a card – Nice graphic design – Gained new knowledge on climate change from the cards whenever I move in the game – The triangle shape applied in the game layout is interesting, and a concept of modularity was used to design the box of this game	– Seldom read the cards; focus on moving and flipping the ice tiles – The game elements should be improved. For example, ice tiles do not fit the board and differentiating the colors of seawater and ice cap is difficult – Excessive trick and teasing; cannot play the game properly – Understanding game instruction is difficult – The knowledge and information provided in the cards have different themes – Poor infographics – The ice tile is substantially small
	Drop 'n' Go	– The action of throwing a waste card into the trash bin – Gained additional knowledge regarding waste separation – Distracted by colors – Nice graphic design, easy to play, excitement is generated when answering the questions – Have various support options and teases other players – Love the rainbow bridge	– Improve readability of the message in the card – Increase types of waste in the cards – Equalize the length of each walking zone – Add support options and a number of players – The game would be more fun if different types of the pathway and additional severe cause and effect of actions are available – Create additional interaction among players

(continued)

Table 19.5 (continued)

Year	Game title	Student reflections	
		Most favorite elements	Further suggestions
	Integro	– The game content is related to real-world situations. The given information is also fact-based. I gained additional knowledge on climate change and awareness of the environmental issues after playing this game – Nice paper cutting and graphic design – Game complexity and excitement of winner uncertainty – Knowledge was smoothly integrated into the game – Colorful and variety of the cards – New playing methods and rules allow various options of strategies for players to customize their playing style – I like the content of this game because it is different from others, especially the system of the game. My favorite part is the bidding session	– The game is complex and needs additional explanation and clarification. The game is long – Some suggestions regarding card applications and hints for the game should be added – Understanding game instruction is difficult. Additional time is necessary to get used to the game. Game rules and methods are learned through play – Have a negative monetary value
2017	7 Disasters	– Nice graphic design and good content – I like the overall theme of this game – The game is interesting and fun to play. I gained additional knowledge regarding environmental issues and many beautiful places in the world – Help with other players to solve the problems; Play with teamwork to collect all the photos – The concept of the game is interesting – I like the Polaroid photos and various types of character cards	– Needs additional prototype testing – Winning is easy and not challenging. The playing methods should be improved – Additional information on the card regarding conservation and rejuvenation of the environment should be included – Have strict rules in the game – Additional excitement should be provided

(continued)

Table 19.5 (continued)

Year	Game title	Student reflections	
		Most favorite elements	Further suggestions
	SusSeat	– The concept of the game is interesting and not boring – Various kinds of furniture design – Provides a considerable amount of information regarding world-famous furniture, including its name, designer, and material used – I like the action of rotating my board – Game flow	– Additional information regarding environmental issues and eco-indicator on the card should be included – Explain a clear meaning of stars and heart on the card – The reason behind positive and negative scores should be described
	Waste Survival	– The concept of metaphor waste is equal to living currency – Nice graphic design – Gained additional knowledge on waste separation and advanced waste management – I like strategic planning and the freedom to choose the card – I like the situation and the consequence card	– The game is less fun due to numerous limitations and strict rules – Reduce the complexity of the game – Focus only on the waste exchange; needs additional related information regarding waste – Improve readability – Add excitement – Needs additional prototype testing

(continued)

Table 19.5 (continued)

Year	Game title	Student reflections	
		Most favorite elements	Further suggestions
2018	Circular Factory	– Nice graphic design and photos for plastic products and waste – I like the game system – Serious strategic planning is required – The concept of circularity is observed in this game – Interesting concept and provides a considerable amount of information – Gained new knowledge while playing – The complexity of the game is exhaustive but fun – This game allows me to plan and produce a product that can be sold. The money can be used to expand my factory	– The system of the game is slightly confusing. Production cost is occasionally higher than product price, which is unreasonable. The game is long – The game is complicated. If the flow can be adjusted, then the game would be really fun – Simplicity is satisfactory. Overthinking while playing makes the game less fun – The game is interesting but its flow is slow. The game would be better if more than one action can be performed in a turn – Additional explanation is necessary before playing the game. I am not aware of the amount of waste I generate. I am only focused on collecting as much waste as possible to produce a product for selling
	Magic Village	– Variety of trash – Various types of cards – The trash in the game is similar to that in everyday life, thus facilitating the easy separation and management of waste in real life – This game is a variation of existing games, this making it easy to understand how to play this game – This game makes provides awareness of waste separation – Nice graphic design. I only knew the separation of wastes into different trash bins – Helps me remember different types of waste	– Differentiating between contaminated and non-contaminated wastes is difficult – Some pictures and graphics are unclear – Apart from players, a checking system should be included to ensure the accuracy of answers. Otherwise, if no one knows the right answer, then everyone will remember the wrong thing

(continued)

Table 19.5 (continued)

Year	Game title	Student reflections	
		Most favorite elements	Further suggestions
	Trash Eater	– Nice graphic design and easy to play – Time constraint when catching ocean trash – Catching the ocean trash in the game – Role-playing in the game as an environmental activist to collect wastes from the ocean – The game is fun and waste collection planning is required to accomplish a personal goal and win the game – The trash-collecting strategy must be well planned to deal with the next consequence cards. A diversity of sea creatures is important in this game	– The fishing hook and trash are substantially small, making these items difficult to catch – I seldom read the information on the card and only attempt to collect as many points as possible to win – The fishing rod is insufficiently weak – Additional information regarding sea creatures should be provided. While playing, I am only focused on obtaining the highest point. By the way, I liked this game the most – The shape of the game box is weird – I am focused only on fishing rather than gaining knowledge on ocean waste, which is the intent of the game

post-tests considering sustainable design principles on the following two groups of students: one with a conventional design project and the other with a game design project. The two potential games (i.e. Integro and Circular Factory) should also be further developed to improve game quality by applying the serious game design assessment (SGDA) framework of Mitgutsch and Alvarado (2012). These games can be used as teaching tools for the next sustainable design course.

Likewise, Oberprieler et al. (2017) proposed that individuals' learning and growth can be considerably influenced by extending the mechanics and rewards to the real world and integrating fully with the environment. The results demonstrated that game design elements and mechanics can potentially be alternative tools that can be integrated into sustainable design guidance, information, and education. In addition, these themes can be applied as an early contribution framework of sustainable design learning experiences.

19.5 Summary

Results obtained from this study indicated that using gamification in sustainable design pedagogy can amplify learning outcomes. However, the outcomes depend on three factors, namely, the complexity of rules, the adequate prototype testing in phase 3 of the gamification design system, and lack of knowledge gain due to physical actions and game tasks. Gamification can be an innovative approach that combines design guidance and environmental information to provide a learning tool for industrial design students. In this way, students can learn through playing and designing. As this approach is at the early stage of intervention in this field, further research is needed to integrate systematic gamification fully into the learning environment and incite individuals' real-world behavioral change.

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Chapter 20
Consideration of Communication Methods with the Next Generation for Sustainable Living Through the Case Study of a Visiting Lecture

Shota Tajima, Satoko Nasu, and Daisuke Fujikawa

Abstract Energy-saving features of buildings are often promoted as a countermeasure against climate change. In housing, not only is the performance of the building important, but social awareness is also needed to encourage people to lead a lifestyle that consumes less energy. As part of the international sustainable housing competition called the Solar Decathlon, the authors of this paper prepared and conducted a visiting lecture for elementary school students aimed promoting awareness of and interest in future sustainable housing. This paper describes a visiting lecture that was conducted by university students of the Faculty of Engineering in collaboration with the Faculty of Education at Chiba University in Japan and examines communication methods that can be implemented to teach sustainability to the next generation of society.

Keywords Visiting lecture · Eco-housing · Net zero energy housing · Sustainable education · Solar decathlon

20.1 Introduction

20.1.1 Background

Measures to fight global warming have led to the spread of sustainable housing. One type of next-generation housing, net-zero-energy, creates all of the energy needed for living via solar power equipment installed in the home, virtually eliminating external energy consumption. The authors of this paper participated in a net-zero-energy housing competition called the "Solar Decathlon" under the team name Chiba University Japan (CUJ) in Spain in 2012 and France in 2014 (Fig. 20.1). At these competitions, we studied the energy saving performance, architectural design, and

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Fig. 20.1 Solar decathlon in Spain, 2012

construction of net-zero-energy housing. During the competition, we conducted a public tour to raise social awareness about clean energy. During our efforts, we had the opportunity to consider the importance of social awareness, which is an issue that people should be aware of whether or not they have any connection with green technologies. In Japan in particular, there is insufficient communication with the next generation regarding social responsibilities. It is therefore important to engage young people because they will be responsible for tackling climate change and other issues in the future.

20.1.2 Purpose

The aim of this study was to consider methods of communication with the next generation regarding sustainable living. Here, we present a case study of university students giving a lecture addressing issues related to sustainability. This study was a cross-disciplinary project in which graduate students in architecture and undergraduate students in pedagogy (education) collaborated as Team CUJ.

20.1.3 Literary Review

Our work builds on previous studies. In example of practical research in actual educational settings, Tanaka et al. conducted a questionnaire survey for aiding the development of a living environment learning program that including the practice of sustainable housing and lifestyle practices in school education with an emphasis on sustainable architecture (Tanaka 2011). Another report described practice using a picture book on the theme of living together and environmental coexistence in high school home economics (Tanaka 2010). In a practical example outside the setting of classroom education, Taguchi reported on the improvement of “town environment literacy” in a children’s building group (Taguchi 2012). In the practice of forest environmental education for university architecture students, Toda et al. investigated the effect on students and clarified not only the recognition of the value to nature but also the effect of communication between participants (Toda 2012). At an Architectural Institute of Japan symposium, Akiyama et al. gave a presentation on interactions of the educational field, industrial world, and society on architectural education (Akiyama 2003). Hikiji used a homemade robot during a visit to a junior high school on a remote island. The students and their teacher worked together to build the robot, demonstrating its usefulness in fostering imagination (Hikiji 2009). More conceptually, a follow-up survey was conducted with junior high school students to examine the effects of environmental education incorporating Life Cycle Thinking in elementary schools (Kasai and Araki 2016). In an overseas case study, Makino and Komatsu researched the programs and teaching materials of a group that provides architectural education to children in the United States. It was revealed that professional organizations related to architecture worked to raise children’s interest in and understanding of architecture through education (Makino and Komatsu 2014). Also, class visitations in the United States have been found to help children who are not good at science to develop an interest in and motivation to study science (Inaba 2006).

These studies demonstrate a multi-sector approach in visiting lectures for both environmental education in architecture toward the realization of a sustainable society. In the United States, organizations such as the American Institute of Architects are actively involved in providing this type of education, which sometimes even includes debates. Because the content that is delivered is different from what the school usually provides, there may be certain on-site requirements. It is also important that the children respond positively to the lecture. However, the approach remains under development. Confirming the validity of the approach will be required before it can be widely adopted.

20.2 Method

20.2.1 Solar Decathlon

This research examines communication regarding sustainable living with the next generation of society, using an example from the Solar Decathlon. The Solar Decathlon was launched by the United States Department of Energy in 2002. It has been held in various parts of the world such as the United States, Spain, France, China, and the United Arab Emirates. At the tournament, 20 university teams from around the world compete to design and build net-zero-energy housing, assembling their creations at the competition venue. After completion, they measure the energy saving performance of their building for 2 weeks. In addition, the participating teams conduct a public tour every day, providing guidance and commentary to the general public, including other university students, construction engineers, and government officials. This provides a great opportunity for hands-on learning about ingenuity in energy efficiency and sustainability.

One of the aims of the competition is to raise social awareness about clean energy. Therefore, emphasis is placed not only on energy conservation but also on the social effects of education focused on energy efficiency and sustainability. Thus, one of the 10 contests comprising the Solar Decathlon is called “Communication,” which stipulates that participating teams conduct public relations activities for various age groups before the tournament. Accordingly, approaches engaging elementary school students have become common for many teams as a way of inspiring future careers in sustainable industries.

20.2.2 Case Study of CUJ’s Visiting Lecture

Figure 20.2 shows various approaches for teaching children about sustainability. Education may be delivered by schools, universities, technical colleges, companies, museums, and non-profit organizations. Methods of delivery include visits to sustainable homes and eco-schools as well as comprehensive learning, and project-based learning.

As part of Team CUJ’s participation in the Solar Decathlon, we developed a lecture to encourage thinking about future sustainability for students at an elementary school in Ichihara, Chiba Prefecture, which is the subject of this research (Fig. 20.3).

The CUJ lecture was developed and presented by 11 university students who were either graduate students of architecture or undergraduate students majoring in education. The lecture was given in October 2011 to 150 fourth graders during an integrated studies class.

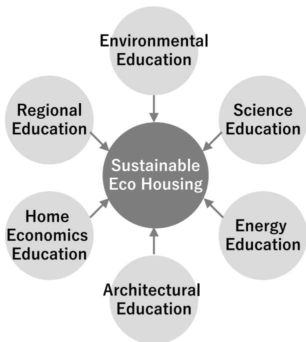

Fig. 20.2 Various approaches to children’s education regarding sustainability

Fig. 20.3 Team chiba university Japan's visiting lecture at an elementary school in Ichihara

20.3 Results

20.3.1 Development Process

In collaboration with companies in the IT field, Team CUJ conducted classes in which the education undergraduates considered the ideal state of school education while also touching on actual societal conditions (Fujikawa et al. 2014). We focused on developing a fun class combining lectures and workshops. In lectures for elementary school children, it is important to include an element of fun, such as through games and group activities (Abe 2016).

During the developmental phase of the visiting lecture, the graduate architecture students took on the teaching role when conducting mock lessons with the undergraduate education students, who played the role of elementary students. To attract student interest, "Students aiming for the world published in the newspaper" was proposed as a lesson theme. Newspaper articles reporting Team CUJ's work were used in the lesson planning phase. In one workshop, we decided to use a copy of an article displayed on large art paper depicting a sustainable housing concept designed by children.

Table 20.1 lists each component of our visiting lecture at the elementary school in Ichihara. First, we presented a short lecture about sustainable living. Then, the children were given time to freely draw pictures based on the theme "Future housing that is kind to people and the environment." Finally, a questionnaire was conducted to evaluate the children's responses to the visiting lecture.

Table. 20.1 CUJ's visiting lecture in detail

	Content	Method	Time (min.)
1	Mini-lecture on sustainable living	Presentation on proposed model housing	45
2	Workshop to develop own proposal	Group work session - drawing a person and an environmentally friendly house of the future as a group Group presentation session - designing a poster presenting the group's proposal	45
3	Questionnaire	Five questions with five-point scale and free description	20

All content was completed in one visit

20.3.2 Questionnaire Results

Figures 20.4, 20.5, 20.6, 20.7 and 20.8 show the questionnaire results. The questionnaire was analyzed by simple aggregation, text mining method, and correlation between questions.

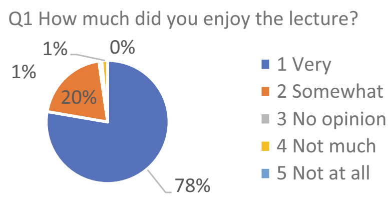

Fig. 20.4 Responses to question 1

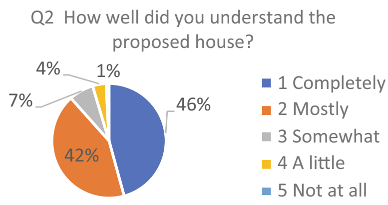

Fig. 20.5 Responses to question 2

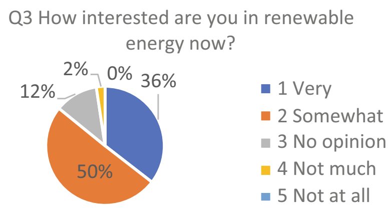

Fig. 20.6 Responses to question 3

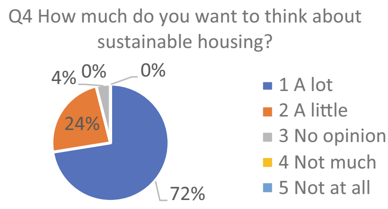

Fig. 20.7 Responses to question 4

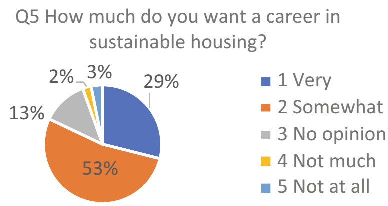

Fig. 20.8 Responses to question 5

In response to Question 1, 98% of children answered that the visiting lecture was very or somewhat enjoyable, thus confirming that the visiting lecture was fun for this group. Regarding understanding of the proposed housing in Question 2, 88% responded that they understood very well or somewhat. This indicates that the idea of the proposed housing was generally transmitted. Question 3 addressed interest in renewable energy, for which 36% responded that they were very interested and 50% somewhat interested. Thus, interest in renewable energy as a whole tended to be high. For Question 4, 96% of responses to how much children want to think about sustainable housing were a lot or a little. Lastly, Question 5 asked if children would like to pursue a career related to sustainability, with 82% of the children expressing such an interest.

Question 6 was a free response and was assessed by a word cloud that included nouns and verbs. The children provided active answers such as "think," "do," and "understand" (Fig. 20.9). We also designed a co-occurrence network diagram from Question 1, which showed that the work of "making," "drawing," and "thinking" about sustainable housing is the reason why the children enjoyed the visiting lecture (Fig. 20.10).

Table 20.2 shows the correlation coefficients between each question's evaluation average and the first question's evaluation average. The correlation coefficient between questions 1 and 3 or 4 was relatively high but that between questions 1 and 2 or 5 was relatively low.

From the results, we understand that the task of drawing and thinking by oneself using the article as a basis, as well as learning about sustainable housing was connected to the understanding and enjoyment of the visiting lecture.

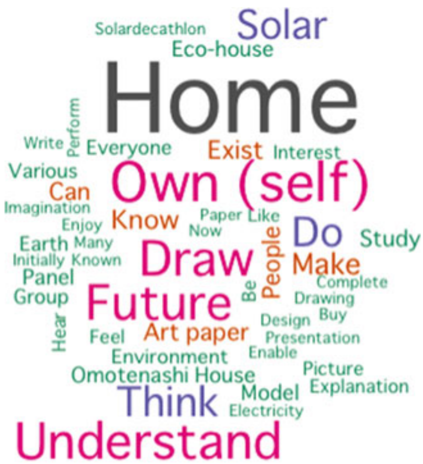

Fig. 20.9 Word cloud of responses to question 6

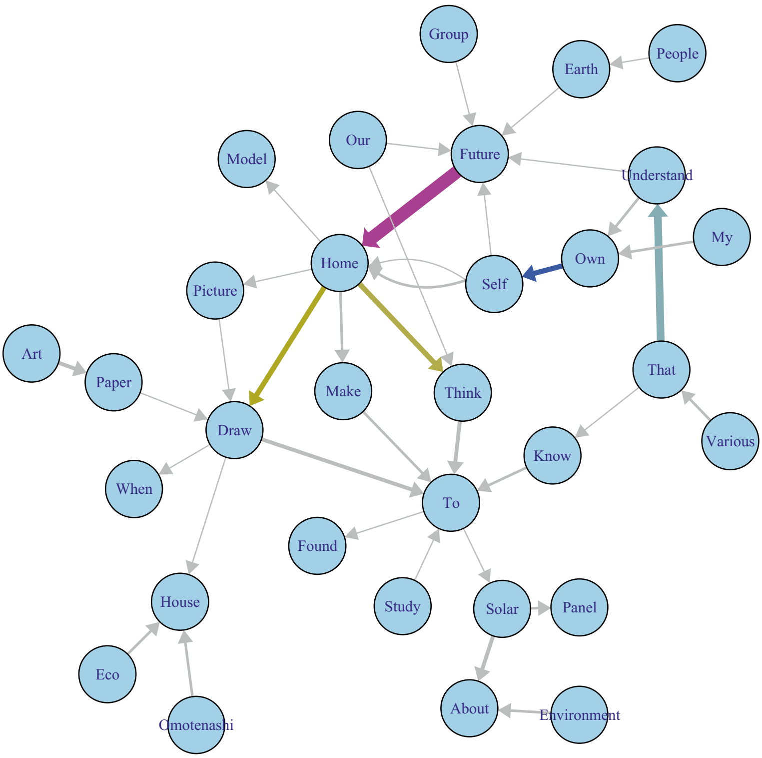

Fig. 20.10 Co-occurrence network diagram of question 1

Table 20.2 Correlation coefficients between each question's evaluation average and the first question's (Q1) evaluation average

	Questions	Evaluation average	Correlation with Q1
Q1	How much did you enjoy the lecture?	1.26	1.00
Q2	How well did you understand the proposed house?	1.71	0.34
Q3	How interested are you in renewable energy now?	1.81	0.51
Q4	How much do you want to think about sustainable housing?	1.31	0.52
Q5	How much do you want a career in sustainable housing?	1.98	0.43
	Average	1.70	0.45

20.3.3 Comparison with Other Countries

Finally, we compared our methods of environmental education for elementary school students with those of other teams participating in the Solar Decathlon Europe 2012 (SDE 2012), sponsored by the Spanish Ministry of Housing. Considering contest item "Communication", SDE 2012 aimed to promote social awareness of the policy that energy efficiency and renewable energy use in buildings are essential for combating climate change. About 5,000 children attended SDE 2012 and learned about sustainability (Navarro 2014). The SDE 2012′s 10ACTION project received the Communication Award for Sustainable Energy Europe from the European Commission, who praised it for inspiring children to pursue careers related to sustainability.

The communication strategy contents of participating teams are described in the form of a project manual. Table 20.3 summarizes the communication methods and strategies used by the 12 teams that participated in SDE 2012.

Five out of 12 teams set a target group. Most teams focused their efforts on children. Many teams conducted visiting lectures, but no details were provided.

As a whole, various methods besides technology and conceptualizing energy-saving housing enabled children to think about the environment, renewable energy, and sustainability. One university that built an actual prototype invited the public to tour the building.

20.4 Discussion

This case study revealed the following considerations.

First, to enable the realization of a sustainable society, an approach incorporating perspectives from both education and social awareness is required (Fig. 20.11). In Japan, as Makino and Komatsu point out, university laboratories and architecture

Table 20.3 Comparison of SDE 2012 participating teams' communication strategies

Teams	Target Age(s)	Means	Activities	Core message
A	Elementary school (Ages 10–11 years)	School visit	Lecture and workshop comprising drawing of desired houses	"To think about making your future house environmentally friendly and sustainable."
B	Preschool (Ages 3–5 years)	Story book	Reading the story book "Looking for the House"	"To serve as an educational aid for parents and teachers when explaining environmental education to children."
	Primary school (Ages 6–10 years)	Drawing competition	A "Thinking Mediterranean" drawing competition based on the one designed by 10 ACTION	"Draw the sun's energy"
	Secondary School (Ages 11–15 years)	10th Science Fair	- A tutored workshop - Reproduce a house at a different scale	"Reproduce House B"
C	Children (Ages 5–11 years)	- Website - Monthly magazine (visibility and media partnership collaboration)	Mascot drawing contest	"To consider the environmental preservation and issues, disseminating in a plain manner the passive, active and dense concepts"
	- Teenagers (Ages 12–19) - Young people and creatives (Ages 19–25 years)	- Social networks - Media coverage	- Contest involving collaboration with a magazine's website - Including consideration of kitchen color and choice of plants and flowers in the garden	- "To suggest solutions on specific topics involving architectural and living solutions for the house." - "Considering passive and eco-conscious concepts such as saving energy, safe use of devices, using materials of low energy."

(continued)

Table 20.3 (continued)

Teams	Target Age(s)	Means	Activities	Core message
D	Secondary school (Ages 11–15 years)	Educational game playing	Creating an educational tool to transmit the main ideas of sustainable development to children	- "To be aware about sustainable development and new housing technologies." - "To be informed about the environment, renewable energy, and sustainability." - "To understand the importance of thinking sustainably in general, and more specifically taking care of the place/city they live in."
E	Youth	Science celebration event	Workshops with young people and students to raise awareness of sustainable housing	"To think about the consequences of our actions on the environment."
F	Children (Ages 5–14 years)	Workshops in kindergartens, schools, after hours lessons, summer camp, and current exhibition venue	- Play (Lego play and drawing) - Primary school groups lecture	- "To learn cooperation and sense of community in a playful manner." - "To discover and understand at an early age the importance of environmental protection, especially in this generation." - "Play together with fellow kids in a smart way!" - "Learn what environmental protection means."

(continued)

associations often provide living environment education on a one-off basis. However, in the United States, foundations, associations, and museums provide education to children and citizens alike to promote interest in and understanding of the role architecture in sustainability (Makino and Komatsu 2014). Based on 10 ACTION, our visiting lecture focused on promoting awareness of sustainability, following the idea

Table 20.3 (continued)

Teams	Target Age(s)	Means	Activities	Core message
G	Children	- School visit - Visit a net-zero-energy house at the competition site	- Presentation in school - Visiting a net-zero-energy house at the competition site and playing educational games	- "Begin to be concerned for the environment so as to become a citizen that understands the need for a sustainable lifestyle and adopt such a lifestyle accordingly." - "Help preserve our environment in routines, and grasp basic knowledge about sustainability"
H	Children (Ages 4–13 years)	- School visit - Visit a net-zero-energy house at the competition site	- Teaching on solar homes - Drawing own house - Plant trees in the school yard - Public tour (Kid's Area)	- "You can use the sun to do your housework! It's fun and cheerful!" - "At this age, sustainability-based life decisions can be made." - "Learn that being "green", or "eco" means taking care of nature."
I	Children (Ages 6–11 years)	Primary school visit, afterschool, classes, and events about ecology and the environment	- Afterschool classes, events about ecology and the environment - Education at school camp activities	- "In the world of children, nature plays a major role. How is human behavior related to the state of the environment and climate change?" - "This is a key question to teaching sustainable living from an early age."

(continued)

of being able to act correctly after becoming an adult. Because the lecture was conducted by university students, their skills are not as developed as those of a professional architect, but the presented content was sufficient enough to raise awareness of sustainable living (as considered from the responses of participating students). In other words, Team CUJ's communication strategy with children was successful. Table 20.3 shows that many of the teams participating in SDE 2012 emphasized environmental awareness rather than learning.

Table 20.3 (continued)

Teams	Target Age(s)	Means	Activities	Core message
	Teenagers (Ages 12–19 years)	Primary and high school class visits	- Class visit to House I - Interactive lecture at House I including the opportunity to experience the house	- "Increasingly independent and distinctive, teenagers choose their own way of interacting with the world." - "By engaging in caring for the environment and living sustainably they set the founding stone of a responsible society of the future."
J	Children (Ages 10–14 years)	Visit a net-zero-energy house at the competition site	More than 1,300 school children visit the House J annually	No information
K	Children (Ages 6–9 years)	Workshops and games	- Drawing the perfect home and light facades - Aim to show the importance of the correct use of energy and sustainability	- "Learning, in a fun and practical way, how housing can save energy and even generate it." - "Become aware, from this young age, how saving energy is important."
	Adolescents (Ages 10–19)			- "Become aware of individual responsibility for saving energy in domestic areas and learn new ways of ensuring a sustainable and self-sufficient building."
L	- Children (Ages 4–10 years)	- Workshops	- Gardening for children - Information and tips regarding vegetables and ecology	- Friendly, pleasant, broad learning

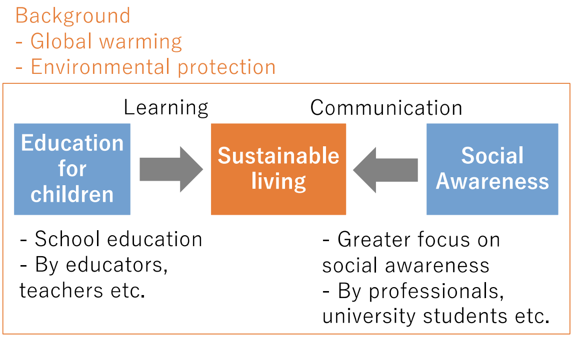

Fig. 20.11 Approaches to sustainable living

Second, visiting lectures have a strong influence on children. The children we visited evaluated our visiting lecture highly in terms of independent learning and learning about building houses while having fun. Furthermore, on-site lessons where people other than schoolteachers can interact with students face-to-face on a daily basis can also have an impact children's future choices. We must acknowledge that the responsibility of conducting such a class is heavy. However, in this study, it was not possible to track the subsequent careers of the children who participated in our visiting lecture. A future challenge is to evaluate whether children have had better understating of eco-living after class.

Third, the method of delivery has a high educational impact on participating students. In university, there are few opportunities for engineering and education students to learn collaboratively. Another of our future challenges is to demonstrate the educational impacts of participating in this kind of program on university students.

20.5 Conclusion

This research introduced the concept of sustainable housing to elementary school children, following the model our team presented at the Solar Decathlon, which is an international net-zero-energy housing design competition that aims to raise social awareness about clean energy. We summarized the contents and results of our visiting lecture, which aimed to promote consideration of future sustainable housing. We also considered methods for communicating the characteristics and importance of sustainable living to the next generation.

During the development phase of the visiting lecture, our team of architecture and education students conducted several mock lectures. To attract the attention of elementary school children, we considered introducing a device and a workshop using published newspaper articles. After the visiting lecture, we analyzed the responses to a questionnaire completed by 150 fourth graders. As reasons for having enjoyed the lecture, the most highly ranked answers were creating, drawing, and thinking. Working on creating future sustainable housing inspired by a copy of an article on previous such efforts was also positively evaluated. Other universities used a method of combining their concept of sustainability with a tour of an actual sustainable house.

In summary, the following issues were considered. (1) Realization of sustainable living requires approaches from both educational and social awareness perspectives. (2) People delivering a visiting lecture must understand its strong influence on children. (3) A future challenge is to demonstrate the educational effects for participating university students.

Finally, we would like to express our gratitude to the elementary schoolteachers, children, and university students who cooperated in carrying out our visiting lecture.

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Part V
Sustainability Assessment and Indicators

Chapter 21
Progress for Life Cycle Sustainability Assessment by Means of Digital Lifecycle Twins — A Taxonomy

Theresa Riedelsheimer, Sabrina Neugebauer, and Kai Lindow

Abstract To understand and optimize the impact of a product along its lifecycle, the consideration of social, economic and environmental factors is of increasing interest for customers and regulating institutions. In this context, Life Cycle Sustainability Assessment (LCSA) is used to monitor and understand the trade-offs of the three sustainability dimensions. Today, LCSA still faces major challenges, such as availability, actuality and validity of data or consistent and appropriate measures to support Design for Sustainability. New technological innovations may support the enhancement of the methodology. In the background of a digitized product and service lifecycle, especially Industry 4.0 technologies, Digital Twins and the integration of Artificial Intelligence may solve data and feedback challenges through new ways of data collection, transfer, validation and intelligent analysis. This paper aims at exploring this potential of new technological innovations for an enhanced LCSA of capital goods and durable consumer goods as well as related services and proposes a taxonomy. Therefore, a literature review to identify existing digital solutions and research gaps is established. For the identified gaps, a new concept, the Digital Lifecycle Twin for LCSA is presented. The authors address both, the positive but also the negative implications put on the LCSA framework from a sustainability perspective. Ultimately, these findings will contribute to the enhancement of the LCSA methodology as well as to the design of a support system to enable environmentally and socially sound design of products and services.

Keywords Life cycle sustainability assessment · Digitization · Digital solutions · Digital (lifecycle) twins · Artificial intelligence

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21.1 Introduction

The sustainability impact of products depends on the social, economic, and environmental implications caused throughout the lifecycle. Life Cycle Sustainability Assessment (LCSA) is used to monitor and understand the trade-offs between the three sustainability dimensions, providing customers, regulating institutions and decision makers with information on the sustainability performance of products. The results of the LCSA support legislators as well as decision makers during the product's life to optimize the sustainability of products or systems. Decision support systems use the LCSA results as an input and help, e.g. product designers, to make more informed and sustainable decisions. Nevertheless, this process does oftentimes not exhibit a continuous data flow and is very time consuming for users.

This paper aims at exploring the potential of new technological innovations for an enhanced LCSA of capital goods and durable consumer goods as well as related services. A taxonomy is developed based on a literature review to classify existing and future technologies, which aim at enhancing the LCSA.

21.2 Challenges of LCSA

On the way to a more efficient, dynamic and automated LCSA and sustainable decision-making, various challenges need to be addressed.

LCSA is the combination of Life Cycle Assessment (LCA), Social Lifecycle Assessment (S-LCA) and Life Cycle Costing (LCC) and consequently covers the three pillars of sustainability: society, economy and environment (Kloepffer 2008). The term LC(S)A is used within this paper to refer to the LCSA as well as its elements or only one element of the three (LCA, S-LCA or LCC). The LCSA mainly evolved from the classical LCA, the only standardized method. The LCSA process is structured into four phases: the goal and scope definition, the lifecycle inventory analysis (LCI), the impact assessment and the interpretation (DIN EN ISO 2006). Subsequently, the main challenges, which could be identified in literature, are presented for each phase in Table 21.1. These challenges are mainly identified based on (Kloepffer 2008; Guinée 2011; Finkbeiner et al. 2010; Neugebauer 2016). A consistent approach across all three pillars and the definition of system borders through all product lifecycle phases are crucial for the goal and scope definition. During the LCI and data collection phase, the most significant challenges are related to the availability of data and measurability of social parameters. The lack of consistent methods and the large range of indicators hinder the analysis and impact assessment. The key challenges for the interpretation and communication of the results is their complexity and the interdependency of design decisions and sustainability impact.

General challenges occur from the missing methodological consensus and standardization of the S-LCA framework as well as from the oversimplification of the LCC method with its limitation to economic costs and the negligence of broader

Table 21.1 LCSA phases and the identified main challenges

Definition of goal	
• Complex definition of consistent system boundaries with relevant inputs and outputs • Different types of reporting systems and methods for the LCA, S-LCA and LCC	• Lack of consideration of future dynamics in the common attributional modelling approach • Lack of holistic tools for the assessment
Life cycle inventory (LCI) and data collection	
• Data availability: limited economic data, lack of product specific data and company-external data exchange and fragmented representation of supply chains • Inconsistent data sources, especially when bridging the three dimensions • Inaccurate measurements of dynamics in indicators due to static method architecture and lack of actuality of data • Diverse data formats, data quality and context	• Questionable trustworthiness, granularity and quality of data • High effort for mainly manual data collection • No guarantee of secure data storage • Measurability of social indicators and regionalization of data (e.g. definition of fair wage) • Missing information for a holistic and robust future consequential modelling approach
Analysis and impact assessment	
• Lack of consistent impact assessment methods and characterization factors for the three dimensions	• Complex interconnection and dependencies of the different indicators representing LCA, LCC and S-LCA • No consensus on appropriate indicator sets
Deduction of measures and interpretation of results	
• Complex trade-offs and direct and indirect dependencies between the three dimensions • Challenge of automated and consistent deduction of measurements and feedback	• Complexity of identifying design dependencies between product design decisions and measured sustainability impact • Lack of real-time assessment and real-time support
Communication of results	
• No consideration of different types of communication channels (e.g. machine to machine, machine to human)	• Lack of providing individual and selected results tailored to specific groups of users • Complexity of LCSA results

economic aspects and impacts. The subjectivity of social data provides further challenges for the comparability of results derived for the different dimensions. This requires larger amounts of data. New technological innovations have the potential to address these challenges and support further enhancements of the LCSA methodology.

21.3 Literature Review

The execution of LC(S)A, especially the LCA, is supported by a wide range of digital software tools and databases. Current research is focusing on methodological improvements of the LCSA, but also on its technological support. First literature reviews with a focus on the use of Big Data, LCA and data collection have been executed (Mieras et al. 2019; Song et al. 2018; Cooper 2013). Nevertheless, a holistic review of progress of LCSA from a technological perspective is still missing.

Therefore, a systematic and extensive literature review is conducted to answer the following questions:

- Which current digital solutions exist for LCSA and how can they be categorized and clustered?
- Which challenges of LCSA do those digital solutions address and which may they solve?

21.3.1 Approach

The following steps were executed for performing the literature review:

1. Explorative search of relevant papers in the field of new technologies with the objective to enable progress in LC(S)A, which resulted in 10 papers,
2. Keyword analysis of these papers and categorization of abstracts, which led to the following clusters: (I) approach (LCA, LCC, S-LCA, LCSA) in focus and (II) technologies considered,
3. For each cluster, the sub clusters were identified and respective search strings defined. Cluster II includes the technological trends AI, Big Data, Blockchain, Cyber-Physical-System (CPS), Digital Twin (DT), and Internet of Things (IoT),
4. The respective search strings were defined and the search has been conducted in the database SCOPUS, which is one of the leading databases for scientific research.
5. The resulting papers (in total 180 papers) for each combination of search strings were then filtered for relevance and the abstracts of the remaining relevant papers (110 papers) were read and analyzed.

21.3.2 Results

The results of the literature review were analyzed in two steps. First, the overall number of papers per cluster and the papers with overlapping research topics from different clusters were identified. The overview is shown in Fig. 21.1. The nodes show the search term and the number of related papers in brackets. The number of papers, which treat two search terms is depicted on the edge between two nodes. The analysis of the sustainability assessment approach (cluster I, highlighted in green) shows that most papers focus on LCA. The total number of papers of a category may not be equal to the sum of the papers filtered by topic, since some papers deal with multiple topics.

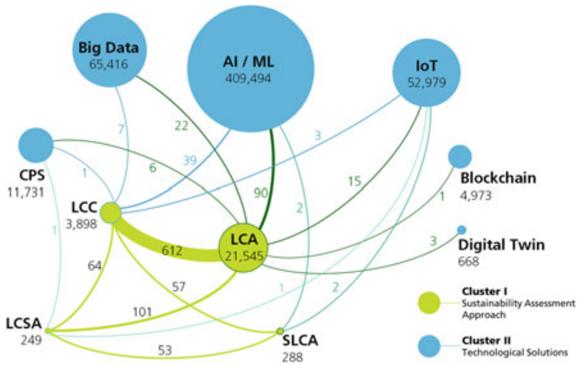

Fig. 21.1 Overview of the results of the literature review

As a second step, all papers, which are part of cluster I as well as cluster II, were filtered for relevance and analyzed in detail. For each category, a short analysis is presented in alphabetical order.

Artificial Intelligence (AI) or Machine Learning (ML)

A lot of research is conducted to improve sustainability assessment by means of AI (125 papers). Most of this research is focused on LCA (90 paper). Two papers also address S-LCA and 39 papers LCC, starting from 1997 with an uncertainty decision support system for gas turbine power generation (Gayraud and Singh 1997). After abstract screening, 48 papers are excluded from the further analysis, as they do not contribute new findings, such as to AI or sustainability assessment, or only present case studies. The remaining 77 relevant papers were analyzed in detail. A high amount of research focuses on the enhancement of decision support systems (46 papers) for specific domains in the planning phase. This includes planning of infrastructure projects, mainly water systems or road networks, product design, manufacturing or process planning and online optimization of maintenance or routing as well as the support for climate change strategies by legislators. Other research applies AI already in the LCI phase to enrich prediction of indicators in future lifecycle phases. Furthermore, AI-research focuses on support during the LCI phase and uncertainty considerations. Due to the high number of papers in this cluster, selected research is discussed exemplarily. Specific examples include multi-criteria decision-making and sensitivity analysis, which is addressed by e.g. using fuzzy reasoning (Chandrakumar et al. 2017). Other research addresses the decision support of product design by integrating LCA-tools into IT-systems from product development and by comparing product variants and their sustainability impact (Buchert 2019). An ant colony optimization-approach is used for sustainable product redesign by optimizing the assembly sequence (Ng 2018). Also, Product Lifecycle Management (PLM) systems are seen as important data source to enhance LCSA with AI (Karakoyun and Kiritsis 2014).

Big Data

28 papers focus on Big Data and LC(S)A, specifically LCA and LCC. Ten papers are not relevant for further analysis, because of only being a review paper (Song et al. 2018) or describing LCSA-case studies of Big Data applications. These are not considered further. Most of the research activities in the relevant papers on Big Data is closely linked to research in the field of AI, which can be explained by the fact that analysis of Big Data demands intelligent data analytic methods. In addition, there is an overlap with the research on DT. The identified research mainly presents Big Data in the context of building and construction projects, smart city or energy generation.

Blockchain

As a specific form of distributed ledger technology, blockchain is proposed by research as one possibility to increase data security. It can theoretically be applied for data collection and secure data storage, especially for sensitive social data, as well as for managing product-specific supply chain data (Abeyratne and Monfared 2016). However, the systematic review reveals only one paper by Smetana et al. specifically mentioning the application for sustainability assessment, namely the LCA (Smetana et al. 2018), which also integrates neural networks and CPS and can therefore be seen as a part of the AI and CPS research.

Cyber-physical Systems (CPS)

In total, only eight papers address CPS and sustainability assessment. One paper specifically considers LCSA with regard to the sustainability of CPS (Gürdür and Gradin 2017), but does not present CPS as a technological solution for LCSA execution. After filtering, only two papers are considered relevant for further analysis. Smetana et al. present a multidisciplinary research on CPS, AI and blockchain (Smetana et al. 2018). The authors discuss the theoretical applicability of blockchain and neural networks for LCA and material flow analysis. They propose an application in food production to monitor material flows. Vanderroost et al. propose a similar concept for food packaging based on data collection with CPS for LCA (Vanderroost 2017), but without AI-consideration.

Digital Twins (DT)

In general, "a Digital Twin is a digital representation of an active unique product […] or unique product service system […] that comprises its selected characteristics, properties, conditions and behaviors by means of models, information and data within a single or even across multiple lifecycle phases" (Stark and Damerau 2019). The review showed no research so far for DTs and LCSA. However, three papers propose approaches for combining DT and LCA. Barni et al. present a DT as an enabler for LCA with a focus on the manufacturing phase (Barni et al. 2018)—a topic of high relevance for this research. Also, Rückert et al. and Wellsandt et al. mention the DT for online LCA without detailing the concept (Rückert et al. 2018; Wellsandt 2017). Nevertheless, all research present the DT as a concept addressing all phases of a

LCA. They enable modelling of product lifecycles (Wellsandt 2017), collection of product-specific primary data via sensors and IoT-capabilities (Barni, et al. 2018), online-assessment (Rückert et al. 2018) as well as domain- and user-specific decision support (Barni et al. 2018; Riedelsheimer et al. 2018). A DT has the capabilities for automatic and autonomous decision-making up to action taking (Riedelsheimer et al. 2018), which can be used for decision support systems.

Internet of Things (IoT)

The search for IoT in the context of LCSA resulted in 18 papers with a main emphasis on LCA. After filtering, ten papers are considered as highly relevant, as they propose new technological solutions for the execution of LCSA (1), LCA (9), LCC (2) and/or SLCA (1). In the analyzed research, sensors are named as enablers for the collection of accurate, product-individual and actual data. Most of the papers focus on energy consumption during Begin of Life (BoL). A highly relevant approach for this research, is presented under the term ubiquitous Life Cycle Assessment by Raihanian Mashhadi and Behdad. The authors propose automated data collection during the manufacturing phase by using sensors and IoT-products on the example of a whole series of hard disc drives (Raihanian Mashhadi and Behdad 2018). Tu et al. propose an approach for a dynamic carbon footprint (CF) based on IoT-technology (Tu, et al. 2017). Garcia-Muiña et al. also use sensors and meters from a digitized production environment (Industry 4.0) as well as the input from manufacturing IT-Systems (MES) for a detailed impact analysis (Garcia-Muiña et al. 2018) in LCA, LCC and S-LCA. Brundage et al. present an analysis of sustainability methods for feedback to design with IoT from the manufacturing phase (Brundage 2018). The research by Kim et al. and Gu et al. focuses on the application of decision support in the End of Life (EoL) phase with data collection via sensors in the use phase (Kim et al. 2017; Gu et al. 2017). In addition, a new conceptual framework for IoT application in LC(S)A is developed by Tao, et al., who present a four-layer model using IoT-technology for data collection and integrating the bill of material (BoM) for data storage (Tao 2014). The solution aims to evaluate product individual energy consumptions along the whole lifecycle. The authors also discuss integration with existing enterprise IT-systems. In a similar approach Tao, Wang et al. present a framework for IoT (Tao 2016). A conceptual framework with different digital tools, that support along the lifecycle to optimize the sustainability of manufacturing systems, is proposed by Cerri et al. (2016).

Summary

In general, the literature review shows a wide scope of research for the application of different technologies in the framework of digitization and Industry 4.0. Against the background of a digitized product and service lifecycle, especially IoT-Technologies, CPS, DTs and AI may solve data and feedback challenges through new ways of data collection, transfer, validation and intelligent analysis. For example, automated data collection with sensors in the context of Industry 4.0 and IoT may supply current data for a real-time LCSA-execution. AI and semantics can be used to identify and analyze dependencies between indicators and support decision making.

21.4 Taxonomy and Gap Analysis

From the conducted literature review, a taxonomy is derived to classify existing and future technologies, which aim to contribute to progress for LCSA and the underlying methods. The aim of the taxonomy is to gain an overview and to assess the current state of research, industrial applications and the future vision for LC(S)A supporting technologies.

21.4.1 Approach

Based on the literature review, the taxonomy is developed and a gap analysis conducted by.

- **Abstract keywording**: Reading all relevant abstracts and extracting the main characteristics that describe the research results presented
- **Keyword clustering**: Grouping the extracted keywords to categories, such as scope, objective, subjective, type of product or phase of LCSA
- **Mapping**: the research findings from the literature review are mapped to the addressed phases of the LCSA and respective challenges (see chap. 2).
- **Gap Analysis**: At last, the gap analysis is conducted to identify unaddressed challenges in research and to derive research gaps for technological solutions.

21.4.2 Taxonomy

The resulting taxonomy with nine categories and respective options is shown in Fig. 21.2. Each technological solution, which aims at enhancing the LCSA execution, can be located within the proposed taxonomy. For each category, one option is chosen. Every combination of the different options is possible.

Subsequently all categories are shortly described:

(1) *Technology and* (2) *Characteristics of technology.*

In this category, the type of technology, which is presented as a solution, as well as its automatic and autonomous capabilities can be classified. This category will be extended with new technologies being developed and applied for LCSA.

(3) *Phase of LC(S)A and* (4) *Aspect of LCSA*

This category represents the traditional four phases of the LCSA-process (DIN EN ISO 2006) and an additional phase, the communication or feedback of the results to the respective user, which can be a human or an IT-system. In addition, it is necessary to specify the, which aspect of the LCSA the assessment is focused on.

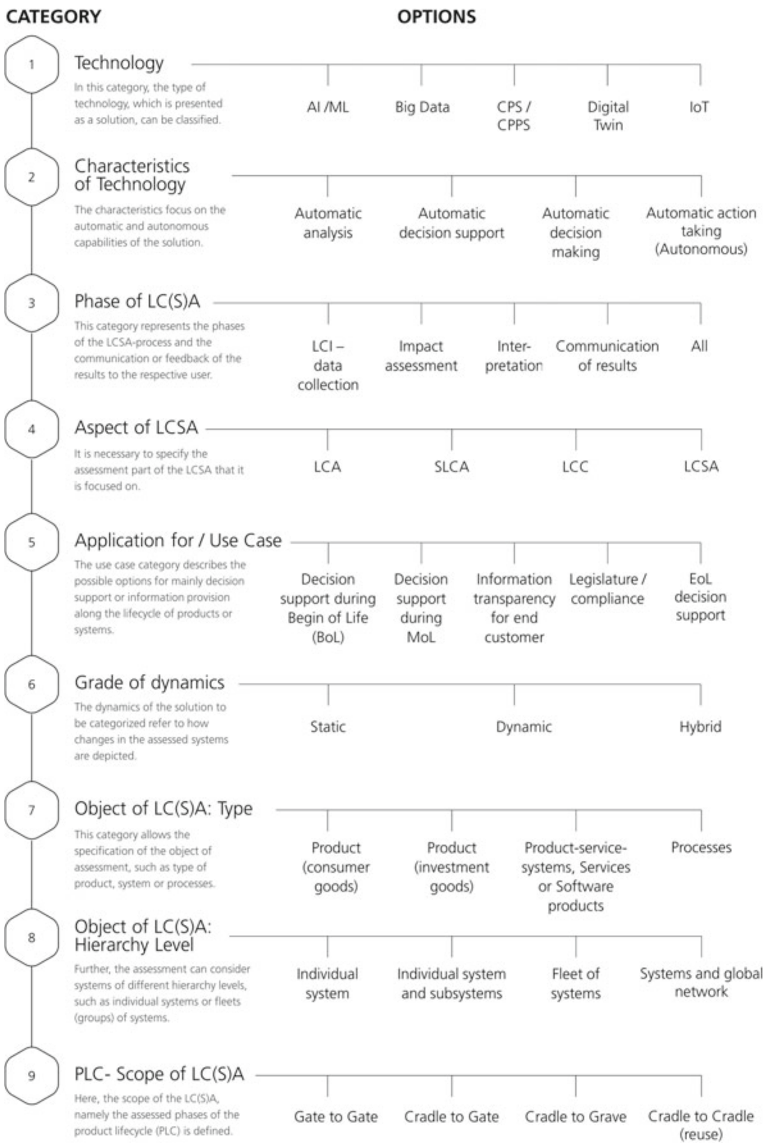

Fig. 21.2 Categories and characteristics of the taxonomy

Some solutions only integrate environmental (LCA), social (S-LCA) or economic (LCC) data.

(5) *Application for/use case*

The use case category describes the possible options of application, mainly decision support or information provision along the lifecycle of products systems. During BoL the product design, production planning or production decisions can be supported. In the Mid of Life (MoL) support for optimized operation, maintenance or information transparency for the end customer can be provided. Another use case is the support of legislation or compliance with regulation and thresholds as well as the decision support during EoL.

(6) *Grade of Dynamics*

The grade of dynamics of the solution refer to how changes in the assessed systems are depicted. Relevant are changes over time, individual systems in retrospective as well as future dynamics, such as changing behavior with changing environment and its prediction. Therefore, prediction algorithms are necessary to allow the representation of future dynamics. The collection of real-time primary data would allow a fully dynamic assessment.

(7) *Object of LC(S)A: type and* (8) *Hierarchy level*

These categories allow the specification of the object of assessment, such as type of product, system or processes. Further, the assessment can consider systems of different hierarchy levels, such as individual systems or fleet of systems, such as a fleet of vehicles for carsharing.

(9) *PLC-scope of LC(S)A*

Here, the scope of the LC(S)A, namely the assessed phases of the product lifecycle (PLC) is defined. An assessment can cover all processes starting from the cradle (raw material sourcing) or the production facilities (gate). The scope can include only the production phase (to gate), the use phase until the disposal phase (grave) or additionally the recirculation (cradle to cradle) (Barni et al. 2018).

21.4.3 Mapping and Gap Analysis

The gap analysis is conducted to understand the focus of current research and to identify research gaps with regard to the challenges of LC(S)A (see chap. 2). A special focus is put on the assessment of consumer goods and their complete lifecycle. For the gap analysis, the two main categories are plotted on the two axes: type of technology and the phases of the LC(S)A with its main activities (see Fig. 21.3). As a next step, all relevant research findings from the 110 papers of the literature review are located within the taxonomy. Blockchain is not considered in the analysis, because the only relevant paper is also part of the CPS and AI sub cluster. As some solutions focus on several phases of the LCSA-process, papers can be listed more than once. In total, 29 phase-specific and 3 generic challenges are defined in chap. 2. For each

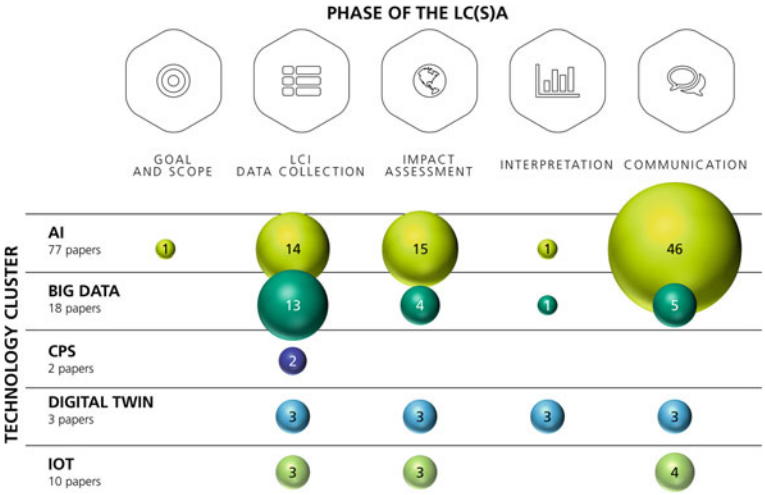

Fig. 21.3 Gap analysis for technologies and phases of LCSA

phase, it is analyzed whether the challenges are addressed in research and if they can potentially be solved by digital solutions or if they are mainly methodical challenges. Overall, the phase with the most research is the communication phase as well as the data collection for the LCI by means of Big Data and AI. Methodical challenges, that are not suited for automation, are not listed in the gap analysis, such as the definition of consistent system boundaries (goal and scope), lacking consideration of future dynamics in attributional modelling or lacking consensus on appropriate indicator sets. Consequently, the following unaddressed or only partially addressed technological challenges are identified:

- **Goal and scope**: Lack of holistic tools for the assessment
- **LCI and data collection**: Measurement of social indicators, incompleteness of supply chain data, lack of product specific data, inconsistent data sources, data formats, context and data quality, lack of actual data for depicting dynamics, highly effortful (partly manual) data collection, secure data storage, lack of company-external and EoL-data, missing information for consequential modelling
- **Analysis and impact assessment**: Lacking consistency of impact assessment methods between the three dimensions and indicator dependencies
- **Derive measures and interpretation of results**: Challenge of automated and consistent deduction of measurements and feedback, complexity of tradeoffs and dependencies between dimensions, complexity of identifying and quantifying design dependencies, lack of real-time assessment and support as well as unused potential of AI to enhance predictive LCSA
- **Communication of results**: Lack of providing individual and selected results tailored to specific groups of users, different types of communication channels

are not yet considered (e.g. machine to machine, machine to human), complexity of LCSA results is challenging to communicate

Additionally, the analysis shows that most applications in case studies are not covering the whole lifecycle (cradle to grave), but only parts of the lifecycle and therefore may disregard important impacts or aspects.

21.5 New Concept Digital Lifecycle Twin

A new concept for a Digital Lifecycle Twin (DLT) that is able to address these open challenges is presented subsequently. As a specific manifestation of the DT, the concept of a DLT is described by Riedelsheimer et al. (2018). Real-time lifecycle assessment is defined as a central use case of the DLT. Related work discusses the DT as an enabler for LCA (Barni et al. 2018) and specifically in the context of IoT (Raihanian Mashhadi and Behdad 2018). In addition, the research findings from the IoT cluster (Raihanian Mashhadi and Behdad 2018; Tu, et al. 2017; Garcia-Muiña et al. 2018; Brundage 2018; Kim et al. 2017; Tao 2014,2016) are seen as important input for the DLT concept.

The DLT addresses the following identified gaps (Chap 4.3) along the LCSA-phases with its key features:

LCI and data collection: Lack of product specific data, no automated data collection.

Analysis and impact assessment: Complex indicator dependencies of the different indicators representing LCA, LCC and S-LCA.

Derive measures and interpretation of results: Complexity of identifying design dependencies between product design decisions and measured sustainability impact, lack of real-time assessment and real-time support, challenge of automated and consistent deduction of measurements and feedback.

Communication of results: Lack of providing individual and selected results tailored to specific groups of users.

A DLT for LCSA is a specific form of a DT. A DLT for LCSA is the digital representation of a system, which collects and analyzes the sustainability information of the individual product's lifecycle from cradle to grave, specifically entailing a real-time, dynamic and product-specific LCSA. Figure 21.4 clarifies the relation of a DLT to different DT types as well as its context and use cases.

The specific vision for the DLT for LCSA is indicated by the location within the taxonomy (see Fig. 21.5). The DLT for LCSA must be able to automatically make decisions, integrates all aspects of sustainability (LCSA) and provides decision support during the BoL-phase.

A DT, according to Stark et al., consists of six different design elements (Stark et al. 2019), hardware, software, data repository, digital models and digital shadow data as well as intelligence. Accordingly, the necessary design elements of a DLT for LCSA are defined as follows.

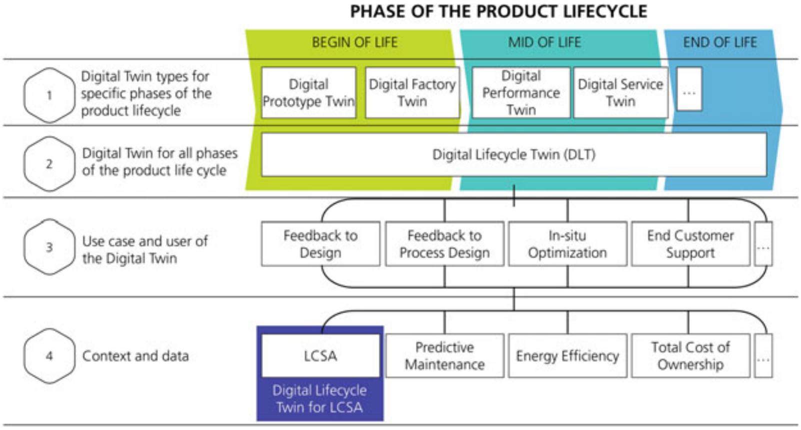

Fig. 21.4 Classification of the DLT

The DLT for LCSA integrates different technological capabilities, such as IoT and AI, and interconnects these along the lifecycle to gain insights on the current sustainability indicators of a system and to derive measures for decision makers within a narrow period. Therefore, a network of sensors near the physical system (soft- and hardware on the edge), IT-Systems (e.g. MES, ERP) as well as third party data sources are interconnected and deliver necessary actual data for the LCI and ultimately the LCSA-indicators. All the primary data is directly connected to the product or system in focus, the so-called Digital Shadow data. Edge devices collect, preprocess and transfer the Digital Shadow data, which is then stored in the DT data repository.

The impact assessment phase is enhanced by the integration of more data sources with actual data and the application of concurrent data analytics. The DLT for LCSA uses the Digital Master and Digital Prototype models from the planning phase to monitor and identify deviations of planned parameters and to draw inferences about necessary design changes and improvements. In addition to the Computer Aided Design (CAD)-models, different Bills of Material (BoM) describe the system on sub-system level including software configuration, manufacturing and service information. On this basis, a decision support system for product design can be implemented.

In summary, the DLT for LCSA can be seen as a real-time decision support system for different decision makers along the lifecycle of a product. By integrating more primary and actual product-individual data in addition to the commonly used secondary data, a better data and information basis for automatic decision making or even a partly autonomous system could be achieved.

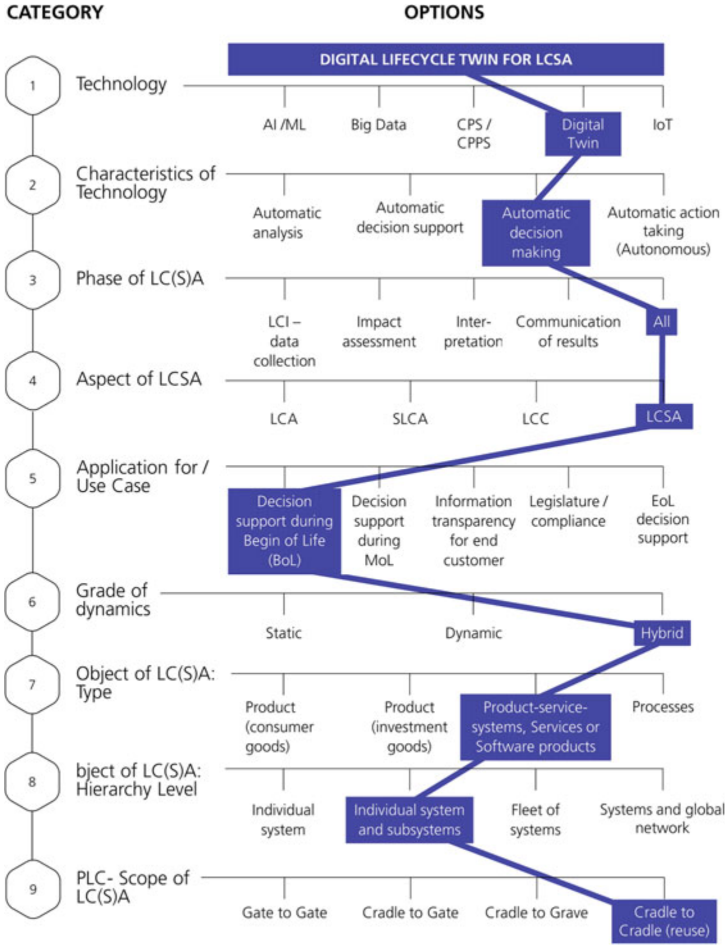

Fig. 21.5 Allocation of the DLT in the taxonomy

21.6 Sustainability Impact and Conclusion

The authors conducted an extensive systematic literature review to identify existing research on technological progress for LCSA. Within a gap analysis, unaddressed challenges are identified and a new holistic concept—the DLT for LCSA—is proposed as a solution to address selected gaps. The goal of the presented DLT is the enhancement of LCSA by increasing information transparency and provision of real-time information on the sustainability of a system. Additionally, by supporting product design decisions, the DLT targets the improvement of the products sustainability performance. However, to evaluate the sustainability improvements, the sustainability impact of the DLT itself needs to be assessed. Due to the fact, that there is no known implementation of a DLT for LCSA, there is also no data basis for an assessment. Questions to be answered in this context are: Can LCSA be applied to an underlying DLT system? Which specific characteristics need to be taken into account? As a DLT is not solely a hardware neither a software product, different requirements might arise. If a DLT is defined as a CPS, the LCSA of a CPS can be used for guidance (Gürdür and Gradin 2017). Other orientations could be LCSA of Product Service Systems (PSS) (Peruzzini and Germani 2013), if a DLT is understood as a system of a physical product and accompanying services.

Future research steps should focus on the elaboration of the DLT concept as well as the sustainability assessment of DLT implementations. In particular, the applicable data structure and information content as part of the DLT for LCSA needs to be defined. Furthermore, existing solutions for integrated and automated decision support should be examined against the adaptability for LCSA. Ultimately, these findings will contribute to the enhancement of the LCSA execution as well as to the design of a support system to enable an environmentally and socially sound design of products and services.

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Chapter 22
Adopting Life Cycle Assessment for Various Greenhouse Typologies in Multiple Cropping Environment in Australia

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Abstract Over the last decades, dramatic population growth worldwide has been directly reflecting in food security. United Nations (UN) projects a world population will increase more than one billion people within the next years, reaching 8.5 billion in 2030. With this anticipated scenario, agricultural industry is experiencing monumental pressures and challenges in adopting and utilising cutting-edge technologies for both open field and controlled agriculture aiming for a sustainable and profitable food production per unit of area of plantation. This study focuses on the controlled agriculture or commonly referring to "greenhouses", which is broadly categorised under three main typologies: (1) low, (2) medium, and (3) high technologies. In general, adopting new materials lead to an increase for both durability and cost of greenhouse structures. Australian horticulture industry has set ambitious and new export targets that would lift export earnings by hundreds of millions of dollars annually. Australian conditions are very different to those that prevail under the northern European climate of the Netherlands, where technologies, associated management systems and accumulated experience were first developed. The study aims to investigate the environmental impacts of a common high technology greenhouse configuration in Australia, which encompasses various infrastructural and production components such as greenhouse structures, soilless cultivation systems, irrigation/fertigation systems, heating/cooling systems, and relevant production applications. The methodology is based on a critical literature review identifying the knowledge gap in Australia, as many studies have been focusing on individual crops in the northern hemisphere. Gaps in life cycle assessment applied to a variety of crops and in high technology greenhouses incorporating green components were identified.

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Keywords Greenhouses technology · Life-cycle assessment · Resource sustainability · Environmental impacts

22.1 Introduction

Despite the human population growth, the agriculture sector is required to produce food, fibre, and biomass energy products under limited resources while reducing related environmental impacts. Caffrey and Veal (2013) cited the main influences from the agricultural segment to the environmental impacts are the land-use change, greenhouse gas (GHG) emissions, eutrophication, eco-toxicity, and human health impacts.

Alternatively, to the open field cultivation, greenhouses appear like an indoor environment suitable to produce a wide range of vegetables or flowers within a controlled condition reducing the risks related to pests, diseases and severe weather. Aiming to target food scarcity in disadvantaged regions, it arises as an important alternative for more sustainable and efficient crop production (Ingram et al. 2017; Jadhav and Rosentrater 2017). The sustainability theme and the social concern about climate change have been increasing within a wide range of industry globally (Wang et al. 2018; Golzar et al. 2018; Santonicola et al. 2018; Shamshiri et al. 2018). In this direction, life cycle assessment (LCA) is an important methodology to quantify greenhouse gas emissions and to assess a wide range environmental impacts of harvest production methods including greenhouse horticulture (Bos et al. 2008; Bartzas et al. 2015, 2017; Goglio et al. 2018).

The DPI NSW (2018) presents some definitions, for example, the glasshouse is the term used when the covering material is glass, and 'greenhouse' or 'polyhouse' denotes the use of plastic coats. Additionally, 'shade house' or 'screen house when the material is interlaced to permit sunlight, moisture and air to pass through the structure and reach the crops. In Australia majority of the industry in currently relies on low technology structures and the most usual are the Tunnel houses, or "igloos" (less than 3-m height) without vertical walls and lack of ventilation. This type of greenhouse is for seasonal and normally operates during the warmer months. Another typology is the medium level greenhouse, characterised by vertical walls, roof and/or sidewall ventilation and clad with either single or double coating plastic film or glass (Department of Primary Industry 2018).

Considering the three typologies, the most innovative is the high technology greenhouse. Burchi et al. (2018) reported a clear definition: "high tech greenhouse is designed to manage, in a controlled and efficient way, different types of crops with different cultivation needs". The high-tech term arises from the greenhouse automation including sensors, data acquisition and analysis via the computational system to optimise crop management, resulting in more accurate information to control the crop environment inputs and outputs, such as impacts to air, water and soil.

This study aims to review the life cycle assessment (LCA) applications within greenhouse crop production in different countries highlighting that Australia is distinctly different in terms of climate, water resources and solar radiation. Additionally, identifying gaps in the literature under the topic of LCA applied to greenhouses including suitable sustainable strategies for protected crop production.

22.2 Methodology

The strategy used in the literature review relies on the Scopus Elsevier Database as the main source for search trustable publications.

Initial search with keywords such as “Life Cycle Assessment” and “Greenhouses” in Title and Abstract fields, limited to English language and Subject Areas including Environmental Science, Agricultural and Biological Sciences, retrieved 756 documents published since 1996 (see Fig. 22.1).

To identify and visualise the most cited keywords and important terms network, VOS viewer software was adopted regarding the simple integration with the Scopus Elsevier Database. Figure 22.2 shows the keywords retrieved from 138 documents close related to LCA greenhouses and published in relevant sources, such as Acta Horticultura, Journal of Cleaner Production, Renewable and Sustainable Energy Reviews and International Journal of Life Cycle Assessment, which was in-depth analysed and discussed in this study.

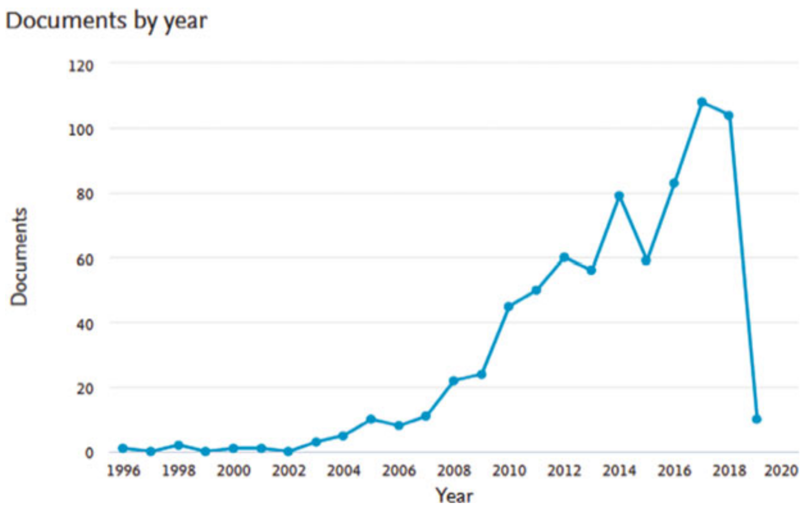

Fig. 22.1 Timeline for the publication’s retrieval with the total of 756 references

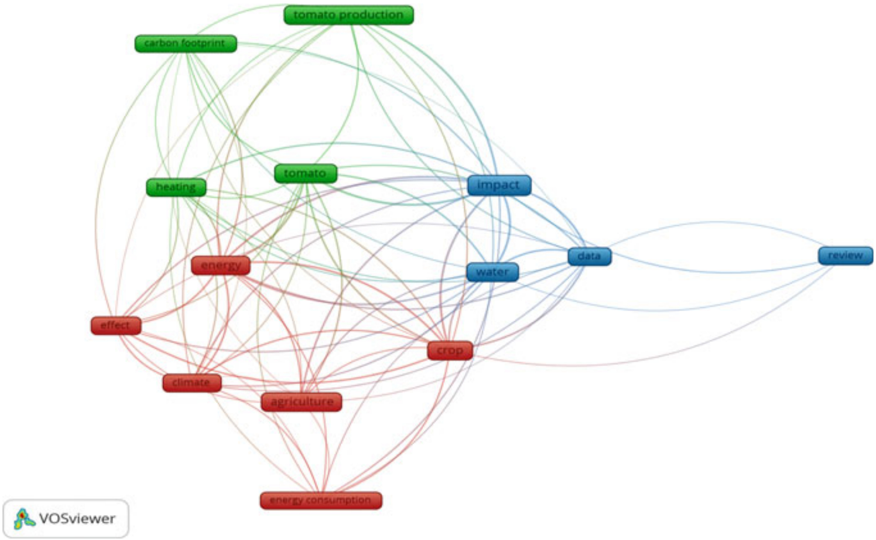

Fig. 22.2 LCA, greenhouse and crop keywords

22.3 Greenhouse Configurations

22.3.1 General Typology

Worldwide is well established that greenhouses are suitable for food production during the entire year. In general, different regions require specific equipment and structure according to the type of crop and construction materials availability (Teitel et al. 2012).

According to Badgery (1999), "a greenhouse should have efficient light transmission, adequate height, enough strength to carry the wind load and sufficient air volume and ventilation to avoid temperature extremes". The shape of the structure influences the greenhouse concerning the quantity of light transmitted and natural ventilation, internal space, structural materials, condensation run-off, cooling and heating.

It is worth to note the research conducted by Page et al. (2011) comparing different types of greenhouses typology in Australia. The authors reported that the average tomato products of 60 tons ha − 1160 tons ha − 1340 tons ha − 1, and 570 tons ha − 1 in open field, low technology greenhouse, medium technology greenhouse and high technology greenhouse, respectively.

The advantages of the modern or high-tech greenhouse are the live acquisition of important data: such as room temperature, humidity, light, carbon dioxide, electric conductivity to measure the strength of nutrients solution, pH and plant temperature. For example, specific sensors are installed for weighing gutter for crop transpiration and chlorophyll fluorescence for photosynthesis. (Hemming et al. 2017).

Following other industries trend, automation of greenhouses has had supplied by modern enterprises, such as Priva and Hortimax allowing productivity increments combined with sustainable management of water, energy and nutrients.

22.3.2 High-Tech Greenhouse Structure

In general, heights of the roof and sidewall in a high-tech greenhouse are 8 m and 4 m respectively, and both will have ventilation mechanisms. Usually, the building materials selected for cladding are plastic film, polycarbonate or glass (Teitel et al. 2012). Some researches, Valera et al. (2017) analysing greenhouses productivity combined with economic performance, depicted the fact of crop management developed on advanced structures does not certainly result in direct increases of these factors. The outcomes showed that the natural ventilation led to higher yield than other climate control systems, at minimum cost.

22.4 Life Cycle Assessment (LCA)

The LCA methodology is based on ISO 14,040 and 14,044 guidelines covering: Goal and Scope aiming to identifies the functional equivalent, system boundary and the set of building materials, Life Cycle Inventory's (LCI) main challenge is the difficulty of collecting reliable and applicable data. In Life Cycle Impact Assessment (LCIA), the quantities of materials, energy consumption, and input data are collected using the environmental impacts indicators. The fourth step is Interpretation to the evaluate the results obtained from LCI and LCIA (UNEP Setac 2009).

During the last years, a variety of software on LCA methodology have been used to simplify the analysis for products and systems, such as SimaPro, GaBi, TEAM and Open LCA. Aiming to provide relevant information about environmental impacts evaluation, this paper illustrates the classification of different midpoint indicators that lead to endpoint categories, as shown in Table 22.1.

According to Cellura et al. (2012), LCA could be used as a decision support tool by three distinct groups:

(a) Product Producers: to improve the environmental performance of a production system;
(b) Product Consumers: to guide purchasing decisions; and
(c) Policy-makers: to inform and direct long-term strategies.

Protected cultivation presents high productivity and high efficiency of most resource usage. Conversely, higher demand and use of water, energy, fertiliser and pesticides result in environmental impacts, such as N-leaching, GWP and energy consumption (Stanghellini and Montero 2012).

Table 22.1 Environmental impacts that lead to human health, ecosystem quality and natural resource (European Commission—Joint Research Centre—Institute for Environment and Sustainability (EC-JRC) 2010)

Midpoint indicators	Endpoint area of protection
Climate change	Human health/ Ecosystem quality
Ozone depletion	Human health
Ionising radiation	Human health
Photochemical ozone formation	Human health/ Ecosystem quality
Particulate matter formation	Human health
Acidification	Ecosystem quality
Eutrophication	Ecosystem quality
Toxicity	Ecosystem quality
Land use	Human health/ Ecosystem quality
Consumptive water use	Human health/ Ecosystem quality
Resource depletion—fossil fuels	Natural resources
Resource depletion – minerals	Natural resources

The environmental impact of greenhouse production for different crops has been published in literature through LCA approaches (Russo and Scarascia Mugnozza 2005a; Russo et al. 2008; Liang et al. 2019; Pons et al. 2015; Dias et al. 2017; Sanjuan-Delmás et al. 2018). According to Perez et al. (2018), several researchers had examined the intensive production of tomatoes in areas with different technological systems in countries such as Switzerland, the Netherlands, Turkey, France or Spain. However, it is important to note that these findings apply to the northeast hemisphere climate characteristics. Nevertheless, a few studies report the state of the art of southern hemisphere, specifically in the context of this study, environmental impacts applied to greenhouse production in Australia (Nordey et al. 2017).

22.4.1 Goal and Scope

This section covers the aims for carrying out, the functional units, the system boundary, reference flows, limitation, data requirements and allocation procedures under ISO 14,044 Goal and Scope. Table 22.2 presents the commonly used functional unit and system boundary. Despite other crops, such as capsicum, cucumber, melon, and eggplant, tomatoes are the most studied product worldwide.

Table 22.2 Examples of functional unit and system boundary

Functional unit	System boundary	References
1 kg of table tomatoes	Typology of greenhouse materials	Russo and Scarascia Mugnozza (2005b)
1 kg of fresh tomato	Cradle to farm gate and included all the direct farming	Page et al. (2012)
1000 kg of vegetables, including the packaging (tomatoes, cherry tomatoes, peppers, melons and zucchinis)	Production and delivery of construction materials for the greenhouses, as well as the production and delivery of chemicals (fertilisers, manures and pesticides), energy resources (diesel) and water	Cellura et al. (2012)
1 tonne of tomatoes	raw material extraction to the farm gate, including material waste disposal	Torrellas et al. (2013)
1 kg of fresh tomato	N/A	Page et al. (2014)
1 kg of packaged tomatoes	cradle-to-gate	Dias et al. (2017)
653 kg of tomatoes	HPS system is replaced by an overhead LED system—incandescent lights are replaced with an LED system	Zhang et al. (2017)
1 kg of fresh tomatoes	Cradle to regional distribution centre approach	Pérez Neira et al. (2018)
11.4-cm begonia plant in a 12-plant shuttle tray	6.6 plants on each square meter of a concrete floor and plants were irrigated using an overhead, traveling boom	Ingram et al. (2018)
1 t of tomato	cradle-to-farm gate	Liang et al. (2019)

22.4.2 Life Cycle Inventory (LCI)

The second phase of LCA is Life Cycle Inventory (LCI) where the information on building materials, energy and emissions are computed (UNEP Setac 2009). In summary, quantified inputs and outputs of a crop production system are included in the whole lifecycle of the greenhouse.

Table 22.3 shows a wide range of inputs considered to the analysis of environmental impacts presented in the literature. It is worth to highlight that the lifespan of the greenhouse materials depends on both intrinsic (materials composition) and extrinsic factors (environmental conditions and use of chemicals).

Table 22.3 Illustration of inputs and life cycle stages

Type of Data/Inputs	Life span	References
Building materials + Energy consumption	Life of structure 10 years	Russo and Scarascia Mugnozza (2005b)
Fertilisers, pesti- cides, electricity and fuel use, water use, rainwater harvesting if any, and typical yields	N/A	Page et al. (2012)
Construction materials,, production and delivery of chemicals (fertilisers, manures and pesticides), energy resources (diesel) and water	Pavilion structures have a life-span of 10 years, while foundations last 30 years	Cellura et al. (2012)
Greenhouse dimensions and agricultural operations, such as crop period, crop density and volume of substrate per bag; as well as water, fertiliser, pesticide, electricity and fuel consumption	The life-span of the greenhouse was estimated as 15 years	Torrellas et al. (2012a)
Fertilisers, fuel, electricity, water requirement, pesticides/and the greenhouse construction	N/A	Page et al. (2014)
Various types of technologies materials and management systems	Lifespan of 25 years	Dias et al. (2017)
Consumption of electricity	N/A	Zhang et al. (2017)
Record of all input products, equipment use, and other activities	N/A	Ingram et al. (2017)
Energy Consumption	N/A	Pérez Neira et al. (2018)
Greenhouse construction materials	10 years in the case of wood and bamboo and 20 years in the case of most other more durable material	Liang et al. (2019)

22.4.3 Life Cycle Impact Assessment (LCIA)

The LCIA includes the calculations, considering quantities of building materials, energy consumption, and emissions to provide the environment impacts results. illustrates the most adopted indicators including abiotic depletion (AD), acidification (AC), eutrophication (EP), global warming potential (GWP), ozone layer depletion (OD), carbon footprint (CF) water footprint (WF), nitrogen footprint (NF), human toxicity (HT) and photochemical oxidation (PO) (Table 22.4).

Table 22.4 Usual impact category and LCIA methods

Method	Indicators	References
CML 2 of 2000	AD, GWP100 OD, HT AP TE, PO, AP, EP	Russo and Scarascia Mugnozza (2005b)
IPCC and Water footprint—methodology by Ridoutt and Pfister (2010)	*CF, WF*	Page et al. (2012)
CML2001 v.2.04	AD, AAP, EP, GWP, POP, Energy use, WF	Cellura et al. (2012)
CML2001 v.2.04	AD, AAP, EUP, GWP, PO, CED, water	Torrellas et al. (2012a)
IPCC	*CF, Energy use, WF*	Page et al. (2014)
TRACI	WF, GWP, OD, EP, Smog, AC,	Dias et al. (2017)
EPA TRACI, CED	GWP, AC, OD, EP Energy use, ecotoxicity	Zhang et al. (2017)
IPCC	*GWP*	Ingram et al. (2017)
CED	Energy use	Pérez Neira et al. (2018)
eBalance v3.0—NF calculations	NF	Liang et al. (2019)

22.4.4 Interpretation

This phase leads to conclusions and recommendations, shows the environmental issues magnitude, and generates appropriate decisions (UNEP Setac 2009). In this study, assessing the case studies retrieved from the most recent literature, word class research groups show that the whole life cycle analysis (typology and crop management) of modern greenhouses are strongly based on embodied energy and operational energy. Regarding this, the LCA of greenhouses main targets presented herein, are building materials, heating system and lighting systems. It does not mean, that other important impacts such eutrophication, water footprint or acidification are less significant. On the contrary, it points the relevance to show the current demand for new studies in order to broadly cover and expand the impact analysis.

(a) Building Materials

Cellura et al. (2012) reported that construction materials, greenhouse maintenance and product packing contribute considerably to the environmental impacts, for example, CO_2 emission. In order to mitigate this impact, eco-friendly raw materials should be selected.

Investigating different types of the materials, Castellano et al. (2008) found that “the presence of glass in the steel structure with aluminium window frames is the main reason for the higher emissions compared to the other greenhouses due to the quantity of metal and energy required to produce it”. The authors’ findings indicated that the greenhouse in wood proved to be the most eco-compatible.

Similar findings were reported by Torrellas (2012b) demonstrating that the materials used to construct the structure have a significant influence on the impact categories, for example: abiotic depletion (50%), global warming (37%), photochemical oxidation (54%) and cumulative energy demand (50%), due to the large amount of steel in the frame and plastic in the covering and floor.

Recently, the impact of building materials on nitrogen emission (NF), was reported by Liang (2019). In China, from 2004 onwards, the construction materials, largely because of the use of steel, but also brick and low-density polyethylene (LDPE), have been the second most important contributor to the total NF.

(b) Heating systems

Dias et al. (2017) presented a GWP of 3.2 kg CO2e/kg of packaged tomatoes, within the range of values (0.24 to 5.1 kg CO2e/kg of tomatoes) published in other studies for a variety of technologies (Table 22.5). It is important to observe that the fuel combustion for the heating system (in this case: natural gas and bunker fuel) accounted for 50–85% of the total impact for ozone depletion, global warming, smog, acidification, and respiratory effects.

In Iran, Khoshnevisan et al. (2014), to evaluate the heating system (natural gas), reported that GWP to produce one kg of cucumber and tomato was 0.244 kg and 0.129.39 kg CO2e respectively.

Perez et al. (2018) compared heated (multi-tunnel greenhouses) and unheated tomatoes production, cited that the annual energy output from tomato cultivation in Almeria (Spain) is estimated to be 246.4 × 103 MJ ha − 1, corresponding to 62.1–37.9% of heated and unheated tomatoes, respectively. Energy (gas, diesel and electricity) (67.7%) and infrastructure (18.5%) are the main factors influencing energy

Table 22.5 Influence of heat system on GWP

Country	GWP kg CO_{2e}/FU	Heating System	References
Spain	0.24	Unheated	Almeida et al. 2014)
France	0.51	Unheated	Boulard et al. 2011)
Hungary	0.53	Thermal water	Russo and Scarascia Mugnozza 2005b)
Italy	0.74	N/A	Cellura et al. 2012)
Australia	*1.7*	*Coal*	Page et al. 2012)
Australia	*1.9*	*Natural gas, coal*	Page et al. 2012)
Netherland	2.0	Combined heat and power	Torrellas et al. 2013)
France	2.0	Natural gas, oil	Boulard et al. 2011)
Northern Italy	2.3	Natural gas	Torrellas et al. 2013)
Canada	2.3	Natural gas	Dias et al. 2017)
Hungary	5.1	Natural gas	Torrellas et al. 2013)

Adapted from Dias et al. (2017)

demand of the heated tomato production, but infrastructure (43.3%) and fertilisation and crop protection measures (25.3%) are the main factors of unheated tomatoes.

It is well known that Australia has the highest average solar radiation/m^2 of any continent in the world. To investigate renewable sources, Page et al. (2014) reported the outcomes of the energy demand of greenhouses. The energy obtained from coal and natural gas were substituted by equivalent MJ through electricity generation in photovoltaic systems for the medium and high technology systems. Regarding this new scenario and the production of one kg of tomato, the carbon emissions from energy sources used in artificial heating reduced from 1.4 to 0.31 kg CO2e and from 1.57 to 0.4 kg CO2e, respectively for medium and high technology. However, more energy is required for cooling rather than heating purpose in Australia. Further research should be carried out in this aspect.

(c) Lightning system

Innovative and sustainable lighting systems are important components of modern greenhouses. Aiming to investigate sustainable alternatives, Zhang and Zaho (2015) (Zhang et al. 2017) compared different light systems, such as high-pressure sodium (HPS), LED and incandescent lights. It is worth to note that the use and consumption of electricity is the largest contributor among all the groups. One exception is the incandescent compared to 18WLED due to the copper component of LED, making it the largest contributor to carcinogenic category. The authors found that LED adoption can result in a net 40% reduction in categories such as global warming potential or cumulative energy demand.

22.5 Summary

From the global scenario in the agricultural sector, it is extensively required new strategies such as sustainable approaches, sustainable materials practices and renewable energy systems to reduce energy and water consumption, GHG emissions, and other environmental impacts of greenhouses crop production.

In Australia, protected cropping is one of the relevant growing areas of food production with almost 30% of all farmers' production in some form of a soilless horticulture system. Recent research, Tingey et al. (2018) reported significant investments and expansion of protected cropping systems concentrated in temperate regions. However, 58% of the total production of high-value vegetables (i.e. tomato, capsicum, cucumber, melon, and eggplant) are supplied from an open field growing region in QLD, WA and NT in the tropics of Australia characterised by climate variability and extreme weather conditions (Tingey, et al. 2018). In this way, more initiatives to research greenhouse crop production and environmental impact in less favourable regions are needed. Page et al. (2012) brought attention to the combination of cropping system and seasoning. The results indicated that in season, low technology greenhouse presents the lowest carbon footprint and overall damage scores at the endpoint level when compared to med and high-tech systems.

It is important to notice that the natural gas, one of the most used energy sources, had been utilised by both cooling and heating systems resulting in significant effects on the environmental burdens. Under this circumstance, it is recommendable to use modern technologies to improve energy use efficiency via automated systems. In Australia, solar energy is an alternative to renewable energy to reduce the usage of natural gas in cooling/heating systems.

Further studies should be considered about the new technologies and design of high technology greenhouses. It is important to evaluate the building components that will be affecting the plant growth, for example, heating/cooling system, lights, site, space and growing media. These components could be designed by adopting the building information modelling (BIM), as a useful platform to gather information on both infrastructure (greenhouse structure) and energy systems.

In terms of the environmental impact analysis considering high tech greenhouse, it is possible to observe that the significant number of publications are focused on Energy demand showing sustainable alternatives to mitigate CO2 emission and/or GWP. However, further studies are needed to evaluate other impacts pertinent to the agriculture industry, mainly water scarcity, and eutrophication in a controlled environment production.

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Chapter 23
Process Modelling for an Efficient and Dynamic Energy Consumption for Fresh Produce in Protected Cropping

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Abstract There are significant research and knowledge gaps on how greenhouse vegetable production can be optimised and the energy consumption can be minimised. In this study, we conducted the analysis of crop production and energy consumption together with the greenhouse climate and local weather records for a capsicum crop in a national high-tech greenhouse facility at Western Sydney University, Australia. The analysis of energy consumption over the production cycle indicates that daily energy consumption varies, due to the seasonal nature of temperature and the need for maintaining desirable temperatures at different growth stages of the capsicum crop. Results also suggest that the system for maintaining temperature using for cooling and heating works within acceptable level of operations. The theoretical and practical implications of this research include the importance of assessing the impact of production cycle on overall performance, and complexities around setting optimum crop production cycles subject to the changing environment. It is concluded that protected crop production provides desired and quality products at estimated times and costs, but further analysis is required for making protected crop production can be adopted by growers in the region, under sustainable conditions of all aspect of resource sustainability. Future research will focus on developing a simulated process model to provide recommendations on appropriate greenhouse practices and crop management in order to effectively manage energy consumption in the protected cropping environment.

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Keywords Process model · Greenhouse horticulture · Capsicum annuum l · Energy use efficiency · Sustainable food production

23.1 Introduction

Protected cropping has attracted increased attention in various parts of the world, due to various reasons and drivers such as advances in greenhouse technology for construction of shelters, meeting increased demand for fresh produce (Torrellas et al. 2012a), better utilisation of water and power consumption (Castilla and Montero 2008), meeting consumer demand for a wide range of products throughout the year (Torrellas et al. 2012b). Furthermore, protected cropping is characterised by high quality and yield of produce, irrespective of climate, weather and soil conditions (Flores et al. 2019), increased reliability of fresh produce supply, and increased choices/options for alternative packaging and presentation with enhanced shelf-life (Smith 2019). Increasing growth in protected cropping is evident from increased take-up of protected cropping throughout the globe, including significant drop in traditional agricultural area, replaced by increased protected cropping in many different countries (Bae et al. 2011), evolving from very simple to complex industrial-type greenhouses in Mediterranean countries (Baille 1997), rapid development of greenhouse vegetable production due to urbanisation (He et al. 2016).

Further, protected cropping is driven by other factors including the need for creating sustainable consumption and production patterns (Borghi et al. 2014), promoting sustainability of the sector, taking consideration of a sustainable waste management strategy, environmental, economic and social aspects (Bartzas et al. 2015). Protected cropping is dominated by the horticulture produce of key varieties including tomato, capsicum, cucumber, lettuce, and eggplant (Almeida et al. 2014; Bojacá et al. 2014; Bartzas et al. 2015; Cellura et al. 2012; Castilla and Montero 2008; Borghi et al. 2014; He et al. 2016; Dias et al. 2017; Torrellas et al. 2012a; Zarei et al. 2017; Ntinas et al. 2017). It is evident that tomato is the most common protected crop across various countries/regions in the world (Castilla and Montero 2008; Zarei et al. 2017). Most of these studies have considered life cycle environment impacts of protected crop and suggest that there are varying impacts of each protected crop, depending of varying yield quantities and total energy consumption (Zarei et al. 2017). Environmental and economic impacts of protected crops have been studied from geographical area perspective, taking into consideration of different climate conditions. For example, (Torrellas et al. 2012a), based on assessment of protected crops in four European countries, indicates that economic assessment in terms of cost is favourable while environmental impacts need to be reduced towards achieving more friendly and healthy production.

In recent times, sustainability in food production is identified as one of the major concerns of growers, consumers and governments, impacting on current practices from different perspectives such as need for further improvement in environmental impacts (Torrellas et al. 2012a), different environmental impacts depending on the type of produce (Zarei et al. 2017) and environmental impacts due to compost produced from agricultural waste (Bartzas et al. 2015). This concern has been exacerbated in recent times, due to increasing population leading to greater food demand (Torrellas et al. 2012a; Dias et al. 2017), increasing businesses' competiveness as well as sustainability in terms of economic development and social well-being (Borghi et al. 2014). From economic perspective, food production significantly contributes to consumption of resources and impacts on environment, where food products are responsible for 20–30% of the environmental impacts of total consumption (European Commission 2006; Cellura et al. 2012; Borghi et al. 2014). On the other hand, it is recognised that there is shortage of vegetables to meet global requirements, in particular under current population growth and apparent promotion of healthy diets (Dias et al. 2017). In this context, greenhouse food production is considered as an alternative approach to food production, not only meeting increasing demand for vegetables and but also operating under certain conditions such as cold climates (Dias et al. 2017). It is evident from various studies on greenhouse food production that focus has been benchmarking of current practices as the basis for improving the industry from the perspectives of energy consumption and environmental concerns (Dias et al. 2017), life cycle assessment of selected food production systems (Blengini and Busto 2009) and environmental and economic assessment of greenhouse crops in cold and warm climates (Torrellas et al. 2012a).

Although protected cropping provides a stable and controlled production environment, energy required for cooling and heating is considered a major overhead expense for maintaining a sustainable operation. Many researchers focused on various types, designs and configurations of protected cropping environment, and benefits of increased quality and high yield crop production. Nevertheless, studies on the energy consumption in the protected cropping environment and its environmental impacts were scarce in the literature. Research studies focusing on protected cropping have reported mainly positive outcomes of selected crops in selected regions, suggesting there is a limited understanding of best practices of protected cropping.

The broader research project of which the first stage reported in this paper aims to address the lack of research into how crop production can be optimised, by selecting a produce that is being considered in high demand, but not considered in previous research within this context. This research is based on a case study of protected crop production at a selected facility in the local context. The scope of the case study is one cycle of selected crop in the facility and associated energy consumption and crop yield data. Key areas of investigation include exploring the crop production cycle in terms of energy consumption and influence of crop cycle timing for optimum yield production under given environmental conditions. The research background around key themes associated with the topic is outlined next, followed by the research methodology. Key objectives of the research are to:

(i) understand dynamic climate conditions and energy consumption during the crop production cycle, and

(ii) determine relationships between energy consumption, crop yield and climate conditions, as the basis for improving current sustainable practices in protected cropping of the selected produce in Australian context.

23.2 Research Methodology

The methodology adopted for this research is a mixed method of analytical approach and a case study. Analytical approach involves modelling of energy consumption of protected crop production. The energy consumption is evaluated as part of optimising the overall crop production using a case study of selected facility. In this case, analysis is aimed at optimising the energy consumption, subject to environment conditions over the selected crop and cycle time. This is evaluated using data from the facility over one cycle of capsicum production. The analytical approach forms the basis for simulating the crop production cycle as a baseline model, which can be later extended to incorporate what-if scenarios within the broader research project. Thus, key steps include:

1. calculate daily energy consumption during the crop cycle, identifying various key statistics (e.g. peak energy consumption period/s, average energy consumption, etc.), and
2. analyse (both quantitative and qualitative) energy consumption and yield data using key variables, in particular specific temperature ranges.

23.3 Data Collection, Results and Analysis

The analytical approach adopted in this research is illustrated using a complete cycle of protected crop production of the facility selected for this research. Data collection, including data collection methods and analysis of data associated with each step are presented under each of the following steps.

Step 1: Identification of protected crop category and key parameters of the crop production

Capsicum plants were grown in the high-tech greenhouse facility at Western Sydney University. The experimental trial was conducted from 23 August 2017 to 4 May 2018, with 3 Capsicum varieties from Syngenta—Waltz (red, 4 rows), Giallo (yellow, 3 rows) and 6412 (orange, 1 row). Plants were grown in Grotop Expert rockwool slabs (100 cm L × 20 cm W × 7.5 cm H), with 4 plants/slab, 3 stems/plant. The greenhouse facility used for capsicum crop comprises of 8 rows/gutters, where each gutter has 32 slabs (except for the last gutter with 31 slabs), making a total of 255 slabs. Pest and disease management was executed by Integrated Pest Management, mainly using biological control agents. Fruit was harvested weekly and the total weight from each row and number of fruit were recorded. Data were calculated and the yield was expressed in kg/day or kg/m^2 per year.

Step 2: Collect and calculate daily energy consumption during the crop cycle

Energy consumption comprises mainly of two components: cooling and heating of the facility during the entire crop production cycle.

The crop cycle selected for this research study starts from 23 August 2017 to 4 May 2018. Key variables for measuring and evaluating energy consumption are recorded every 5 min during the entire cycle, by a controlling system (Priva) that maintains the required temperature and other conditions in the facility throughout the production cycle. Cooling of the facility is facilitated through a combination of fan and pump system of water circulation. Details of key variables associated with cooling are shown in Table 23.1.

Heating of the facility is facilitated using heating water and circulation of heated water through two networks of water pipes (Return 1 and Return 2). Details of heating system including description of key variables and unit of measures are given in Table 23.2.

There are two heating systems using water lines: 1 (wall) and 2 (floor). There is no heating demand during the summer. Heating pump power consumption. (0.17kw, single phase. 1 for wall and 1 for floor). Since power consumption is recorded every 5-min interval, average consumption is evaluated using meter readings of respective systems (Floor and Wall).

Table 23.1 Key variables of cooling at the protected crop facility

Variable	Unit of measure	Description	Details
Fan and pump (F&P) active	Active or Non-active	Fan and Pump—ON/OFF	Water is circulated if required Involves multiple stages Variable F&P is a binary variable. Record of 1 means both fan and pump is ON
Cooling active	Active or Non-active	Fan is ON/OFF	This is a binary variable. Record of 1 means fan is ON
Meas F&P temp	Celsius (°C)	Measured F&P temperature	This variable is the same as the corresponding variable in the environmental data set
Temp F&P active	Celsius (°C)	Temperature setting to activate cooling	This temperature setting is changed as crop matures. This could be based on advice from growers

Table 23.2 Water heating, data collection period: 30/08/17 to 05/05/18. Two heating networks: return 1 and return 2

Variable	Unit of measure	Variable Description
Meas heat t	Celsius (°C)	The calculated value determined by priva based on the user settings and other influences that have been included
Meas return 1 (Wall)	Celsius (°C)	The measured water temperature on the return line of the heating pipes (at exit) on the wall. This measurement point is just before the exiting the room
Meas wt 1 (Wall)	Celsius (°C)	The measured water temperature on the supply line of the heating pipes (at entry) on the wall. This measurement point is just at the entry of wall system to the room (same location as the exit point in the room)
Meas return 2 (Floor)	Celsius (°C)	The measured water temperature on the return line of the heating pipes (at exit) on the floor. This measurement point is just before the exiting the room
Meas wt 2 (Floor)	Celsius (°C)	The measured water temperature on the supply line of the heating pipes (at entry) on the floor. This measurement point is just at the entry of floor system to the room (same location as the exit point in the room)
Wall (system 1) total (KWH)	KWH	The cumulative total kWh consumption for the day of the wall heating
Floor (system 2) total (KWH)	KWH	The cumulative total kWh consumption for the day of the floor heating

Step 3: Analysis of cooling, heating, power consumption and yield data

Since cooling and heating are fundamental aspects for protected crop facility, temperature settings associated with cooling and heating are considered first. It is noted from Fig. 23.1 that cooling system using a combination of fan (six of them running concur-

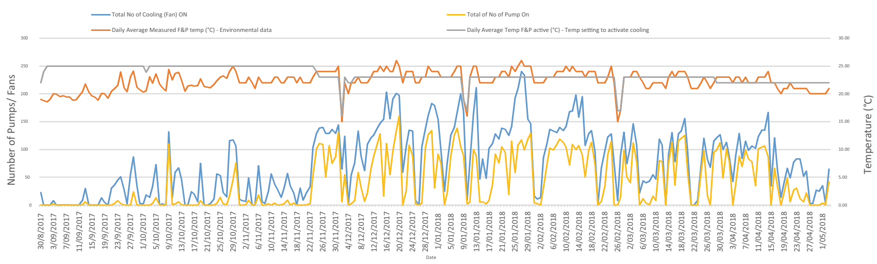

Fig. 23.1 Distribution of temperature (Measured and Active) and average number of cooling fan and pump ONs

rently) and pump seem working well to maintain desired temperature in the facility (Temperature F&P active), for optimal plant growth. It can also be noted from average number of pump and cooling (fan) ONs (active) that both cooling systems (fans and pumps) are synchronised well to maintain desired temperatures. Since the system is set-up to run fans first and pump if required, it is noted that average number of times that fans run are greater than that of pumps active throughout the cycle of operation. This can be an indication of efficient running of cooling system for a protected crop farcicality that is subject to a significant range of temperatures during the plant cycle of 8 months. Since the facility is well maintained at desired temperatures during the whole cycle of more than 8 months, these plants were in a much better conduction considering the outdoor temperature.

We showed that the system is working as expected, by activing the cooling at the right times (Fig. 23.1). Similarly, heating of the facility is considered from the perspective of measured temperature at the facility with temperatures of heating systems. Since there are two heating systems (Wall and Floor) using hot water, water temperature at entry and exit of both systems (wall and Floor) are considered.

It is noted from that heating is very active at the start and end of the cycle, given natural climate conditions during these times. Similar to cooling systems, heating systems are also working as required for optimum plant growth to generate high level yield, compared to crop production under natural conditions (Fig. 23.2).

Since temperature range of fairly large during the start and end of the plant cycle, there is considerable heating power consumption during those times (Fig. 23.3). While the heating is required to maintain the desired temperature for the capsicum crop at the greenhouse facility, investigation into selecting the crop, setting the cycle time with different start time/s and possibility of other influence for changing cycle time is required for optimising the energy consumption.

Analysis of crop production

The selected crop of capsicum of three varieties was started on 23 August and ended on 4 May. The entire cycle includes seeding, flowers, fruits and harvesting. It is noted from yield data that harvesting started on 11 November 2017, after 80 days of the start and continue for about 6 months (180 days). This suggests that harvesting period of the crop cycle is significantly larger than that in usual field crop production.

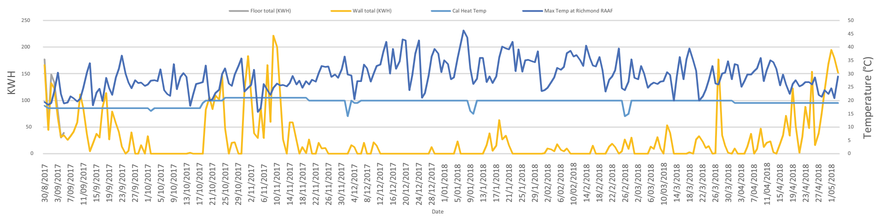

Fig. 23.2 Active and measured temperatures of heating systems

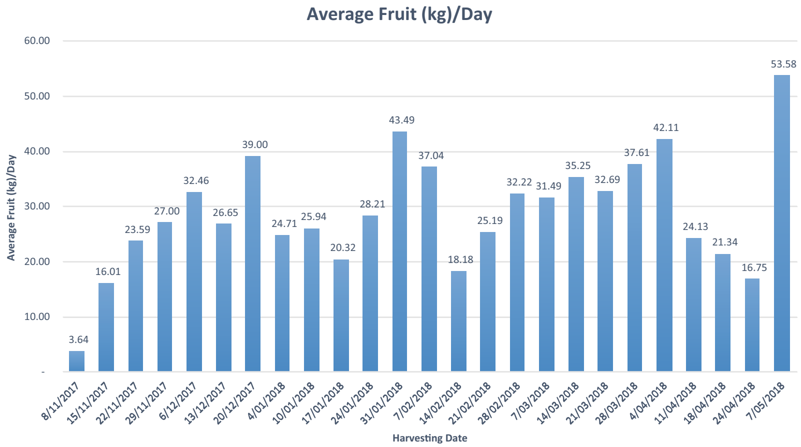

Fig. 23.3 Calculated daily yield of capsicum in a high-tech greenhouse over the 2017–2018 growth season in Richmond, NSW, Australia

Based on the overall yield data over a period of about six months of harvesting (8/9/2017–7/5/2018), average daily capsicum yield is around 30kgs. In this case, the entire cycle is about 257 days, of which the harvesting period is 180 days, which is 70% of the entire crop cycle. Hence, the protected crop cycle itself can be considered as a significantly longer cycle, compared with open field crop production cycles in respective countries/regions. Overall, capsicum yield over the entire harvesting cycle has shown three different peak-to-valley cycles, with individual daily peaks about one to one and half month apart. The significantly increased daily capsicum output (spike) shown at the end of harvesting cycle indicates the harvesting of all yield at the end for the cycle including unmarketable fruits.

Results also show that protected capsicum crop yield is 5.4 kg per plant and about 80.1 kg/m^2 per year. These results, when compared with those of normal horticulture capsicum yield showing that protected crop yields are significantly higher than a typical yield of 53.1 kg/m^2 per year in a commercial greenhouse facility (2000 m^2) in Canada (Guo et al. 2016). The high yield of capsicum over six-month period of harvesting is attributed to meeting all required conditions over the entire life cycle of crop, facilitated through well maintained greenhouse facility. Thus, the protected capsicum crop yield and associated crop cycle can be set as the reference for commercial protected cropping in the local context. Once these results are compared with the global standards, the cycle and yield results can even be considered as benchmarking in the local context.

23.4 Discussion and Conclusions

This study within a broader research study of protected horticulture towards sustainable production and ultra-efficient supply chain of protected crops presented preliminary results of one protected cropping cycle, as the basis for evidence-based information for growers in the region to explore possibilities of commercial protected horticulture. Although protected cropping is shown to be a viable option for meeting increased demand and high expectation of customers for fresh produce, energy required for cooling and heating in the protected cropping is considered a major overhead expense for maintaining a sustainable operation. In this research, the focus was to investigate protected cropping from operational perspectives, in particular analysis of environmental conditions, cycle time and yield outcomes. The analysis of environmental conditions of the selected protected cropping cycle showed that this high-tech facility has so far outperformed those measured in mid- to low-tech greenhouses within the parameters it was set to operate, and the harvesting part of protected cropping cycle is considerable significant. The high yield may also be affected by the small experimental areas (400m^2) and more intensive crop management in our high-tech greenhouse as compared to large-scale of commercial greenhouses, which usually have more than 1 ha in size (10,000 m^2).

In this study, the analysis of energy consumption over the production cycle indicates that daily energy consumption varies, due to the seasonal nature of temperature and the need for maintaining desirable temperatures throughout. A viable comparison was not conducted due to the lack of sufficient literature and comparable publically available dataset. Therefore, further research is required to test the same crop in the same facility with variations in energy saving strategies. Furthermore, protected cropping yield has significantly high, compared to that of normal of cropping of the selected produce. Although cost of energy consumption and other overheads are not considered as it is outside of the scope of this study, future studies are required to investigate the same, so protected cropping can be considered as viable option for growers, not only meeting increasing demand, but also in a long-term economical perspective.

Implications of this research include the importance of assessing the impact of production cycle on overall performance, in particular setting the start of the cycle which can influence the optimum crop production cycle from both environmental and economic perspectives. Furthermore, shifting the start of the crop production cycle will reduce the energy consumption throughout the production, hence meeting the objective of sustainable operation and reducing environmental impacts. Overall, it is expected that protected crop production provides desired and quality products within acceptable costs, but further analysis is required for making protected crop production a viable option for growers in the region, under acceptable sustainable conditions with minimum impact on the environment.

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Chapter 24
CO_2 Removal Using the Sun and Forest: An Environmental Life Cycle Assessment of a Solar & Biomass Hybrid Carbon Capture and Sequestration Plant

Shutaro Takeda, Andrew John Chapman, and Hoseok Nam

Abstract This paper proposes and analyses an innovative sustainable energy option; a concentrated solar and biomass hybrid carbon capture and sequestration plant. This conceptual plant utilizes concentrated solar as the heat source for the biomass gasification process. The produced synthetic gas will then be used for electricity generation and carbon dioxide will be removed and sequestrated in an underground reservoir. With this new energy option, a sustainable future energy system can be designed whereby the carbon removed by the forest can be both utilized and sequestrated using the power of the sun. The environmental impact of 1 kWh of electricity production was assessed through a life cycle assessment using ecoinvent, and the life cycle GHG emissions of the plant were estimated to be −0.812 kg CO2-eq/kWh. This result shows that even at the 95% percentile, net GHG emissions from Solar Hybrid BECCS (−0.492 kg/kwh) is lower than that of a conventional BECCS plant (−0.474 kg/kwh). To summarize, this technologically fusible energy option may have a great potential in achieving energy sustainability towards the 2.0- and 1.5-degree scenarios by achieving carbon removal with the two fundamental gifts from the nature: the sun and the forest.

Keywords Solar · Biomass · CCS · BECCS · LCA · GHG

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24.1 Introduction

Under the auspices of the United Nations Framework Convention on Climate Change (UNFCCC), the Paris Agreement was developed with the central aim to strengthen the global response to climate change, through the control of global temperature rises to below 2 °C above pre-industrial levels. A more ambitious goal is to restrict temperature increases to below 1.5 °C, and to strengthen nation's abilities to deal with climate change impacts (UNFCCC 2018a). The Paris Agreement entered into force in November 2016, and at the time of this study, of the 197-member nations party to the UNFCCC, 176 nations have ratified the agreement and communicated their nationally determined contributions (NDC) or intended NDC (UNFCCC 2018b). According to independent scientific analysis of current climate change policies and NDCs under the Paris Agreement, the change in temperature by the end of this century is estimated at between 2.6 and 3.7 °C. This is an improvement on global warming in the absence of mitigatory policies, estimated at between 4.1 and 4.8 °C, however, current efforts are not ambitious enough to meet the 2 degrees or the 1.5 degrees targets. In order to meet these targets, radical action on climate change is required, reducing greenhouse gas (GHG) emissions rapidly down to zero by around 2050 (Climate Action Tracker 2017).

Decarbonization is the first step toward meeting climate change goals and achieving the Paris Agreement targets. In addition to the decarbonization of industry, transport and building sectors, national energy scenarios provide energy generation options which are carbon neutral (Wind, solar, nuclear) or low carbon (gas, carbon capture and storage (CCS), etc.) to achieve deep GHG cuts by 2050 (Mathy et al. (2018)). However, decarbonization alone is insufficient to reach a net zero emissions outcome by mid-century. In order to achieve zero emissions, energy generation technologies which are carbon-negative need to be introduced to ensure the long-term stability of global temperatures, and the survival of all species on earth. A number of negative emissions options exist, including direct air capture, enhanced weathering and bioenergy with carbon capture and storage (BECCS), among others (Haszeldine et al. 2018). The incorporation of BECCS as a potential solution to keep temperature increases below 1.5 °C has been proposed as part of the Paris Agreement negotiations (Editorial 2018).

In this study, we consider the role of BECCS using the gasification of biomass, with heat provided by concentrating solar power (CSP) to generate electricity. Such a system provides the dual benefit of clean energy on the one hand and offers options for the storage of CO_2 to achieve a carbon-negative outcome on the other.

24.2 Background and Literature Review

In order to achieve the deep cuts in carbon dioxide levels to enhance the likelihood of achieving the sub 2-degree Celsius targets, the vast majority of Intergovernmental

Panel on Climate Change (IPCC) scenarios assume large-scale deployment of carbon negative technologies, including BECCS (Muri 2018). In terms of the potential CO_2 capability of BECCS when used in collaboration with other carbon removal strategies, (Psarras et al. 2017) estimates some 12 giga-tons (Gt) per annum, the same amount as offered by direct air capture at about 1/6th the cost. Along with land management (the cheapest method of CO_2 removal, with moderate removal capacity), BECCS is likely to play a large role in any future carbon negative technology package. In light of the likelihood of BECCS deployment, a number of national, regional and global case studies have emerged, measuring emission reduction and energy provision capacity, along with policy considerations. The literature review is presented in three parts, beginning with national and international considerations of BECCS, CSP and BECCS precedents, and the need for a carbon tax to enable these technologies.

24.2.1 National and International BECCS Research

In Australia, a nation with one of the highest per capita GHG emissions among developed nations, is a signatory to the Paris Agreement, intending to reduce emissions by 26–28% below 2005 levels by 2030 (Australian Government 2015). In order to achieve this ambitious target, renewable energy-based generation is expected to play a significant role. Should the supporting technology of CCS, and the bioenergy sector play a complementary role, BECCS may provide a significant contribution to the supply of energy and reduction of emissions in Australia (Pour et al. 2018). Based on the availability of utilizable biomass in Australia, it is estimated that BECCS could contribute approximately 25 million tons (Mt) of CO_2 per annum in negative emissions while providing 13.7 terawatt hours (TWh) of clean electricity (approximately 3.5% of the projected gross 2050 electricity generation total). In addition to negative emissions and the provision of electricity, BECCS adds flexibility to Australia's fossil fuel dominated energy portfolio. In order for BECCS to be successful in Australia, policies which support renewable energy will need to be extended to BECCS to improve its economic feasibility, while stakeholder engagement is seen as necessary to improve the acceptability of this new technology (Pour et al. 2018).

Brazil, on the other hand has a relatively high renewable energy contribution to its energy system, some 47%, along with significant production of ethanol from sugarcane as an automotive flex-fuel and bioelectricity source. BECCS offers Brazil a technology to enable the removal of carbon in the ethanol fuel cycle, estimated at 27.7 Mt of CO2 per annum, or 5% of emissions arising from energy production (Moreira et al. 2016). Brazil's intended NDC aims to reduce GHG emissions by 43% below 2005 levels by 2030, requiring significant action in increasing biofuel consumption, land use and the reform of the energy, agriculture, industry and transportation sectors (Federative Republic of Brazil 2015). For BECCS to play a role in this future energy vision, financial feasibility needs to be improved through exports of advanced and certified ethanol to the United States (US) and the European Union (EU), respectively, and the deployment of an incentive scheme for domestically consumed BECCS-ethanol (Moreira et al. 2016).

For the US, whose GHG emissions account for 15% of total global emissions, second only to China (30%; (Boden and Andres 2017)), negative emissions technologies may have an important future role in meeting global emissions targets. Initially, the US were a signatory under the Paris Agreement, with an intended NDC of a 26–28% cut compared to 2005 GHG levels by 2025 (UNFCCC 2015). Although the US has since withdrawn from the agreement, under Article 28, the earliest that such a withdrawal could come into effect is in the year 2020, until which the US is obligated to maintain its commitments (UNFCCC 2018b). According to a geospatial analysis of the US suggests that a complete mobilization of all available biomass for BECCS could engender 370 Mt of negative emissions per annum by 2020, however considering limitations of biomass and CO2 transportation and injection limitations, a more realistic technical potential of BECCS is approximately 100 Mt per annum by 2020 (Baik et al. 2018). This estimate is cognizant of biomass production at the county level, CO2 pipelines and storage sites across the US and extols BECCS as a superior negative emission technology because of its positive energy contribution (Baik et al. 2018).

In addition to single nation studies, several global-scale studies of BECCS potential contribution to emission reductions have been undertaken. For example, (Kato and Yamagata 2014) assessed the role of BECCS toward keeping mean global temperature rises below 2 °C, identifying that current generation bioenergy crops (corn, sugarcane, sugar beet etc.) would be insufficient to meet the target. Utilizing second generation (lignocellulosic) bioenergy crops and thermochemical conversion to synthetic natural gas, the BECCS contribution can become effective, only if all resultant emissions are captured and a high-fertilizer approach to crop production is undertaken. In all scenarios assessed, significant additional land use is required (resulting in additional emissions), increasing the risk of a food vs fuel type outcome. In order to ameliorate the identified land use issue, the assessment of bioenergy potential from residues, waste and woody biomass is suggested, along with a concomitant contribution from the forestry sector.

In addition, (Moriarty and Honnery 2016) investigates the role of biomass in reducing GHG emissions under a 'food first' approach considering dietary changes and a shift toward the use of biomass-based materials (biomaterials) and bioenergy. They seek to address the food vs fuel issue and extol the use of multiple sources of biomass as replacements for fossil fuel sources. In terms of policy implications, they identify the large subsidies received by fossil fuels, and the potential advancing of biomass-based approaches, should a carbon tax be realized. Specifically investigating the energy return on energy invested (EROEI) metric, a material, bioenergy and CCS pathway is identified as providing a positive return into the future.

In their investigation of a zero-emission future scenario, (Tokimatsu et al. 2016) identified a series of advanced energy technologies which could be developed and deployed to meet emission targets and achieve global economic growth. By adopting a least supply cost minimization model which considered energy, mineral, biomass and food resources across 10 global regions, the authors identified a significant role for BECCS in terms of heat supply, more than 4000 megatons oil equivalent (MTOE) per annum by the year 2100. In order to achieve the future zero emission scenario which promotes economic growth, particularly in developing nations, it was estimated that renewable energy would play a significant role alongside fossil fuel and CCS based generation. For the transport sector, hydrogen production from coal with CCS was shown to be optimal. Synfuel substitution for gas produced with CCS is also suggested as a complementary approach. In terms of biomass and BECCS contribution, the efficient use of biomass resources is identified as a requirement for a zero-emission future under a least supply cost minimization approach.

24.2.2 CSP and BECCS Precedents

Solar driven gasification has the potential to convert carbonaceous feedstocks into synthesis gas (syngas), a blend of hydrogen and carbon monoxide, easily processed to useful, liquid fuels with lower GHG emissions than conventional gasification or the combustion of fossil fuels. The use of solar energy to convert biomass into syngas reduces reliance on fossil fuel imports for resource-poor nations and provides an easily dispatchable liquid fuel from an intermittent renewable energy source (Piatkowski et al. 2011). Advances in solar concentrating technologies suggest that certain configurations of solar reactors (indirectly irradiated packed-bed, directly irradiated vortex-flow and indirectly irradiated entrained-flow) can achieve temperatures exceeding 1500 K (1227 °C), sufficient for efficient gasification. These approaches remain at the pilot scale (less than 1 MW) and do not incorporate CCS. Successful market entry of such approaches remains dependent on feedstock and fossil fuel prices and subsidies available for pollution abatement and GHG emission reductions (Piatkowski et al. 2011).

Assessing the potential of solar gasification using molten salts, (Hathaway et al. 2011) describes a solar concentrator and molten alkali carbon salt-based approach, capable of molten salt temperatures between 850 and 960 °C. Results are presented at the laboratory scale and suggest that the temperatures achieved improve pyrolysis levels of biomass and gasification efficiency, extoling the virtues of using the alkali carbon salt. The exploitation of this proposed approach would be dependent on the incorporation of a CCS component and the ability to scale-up.

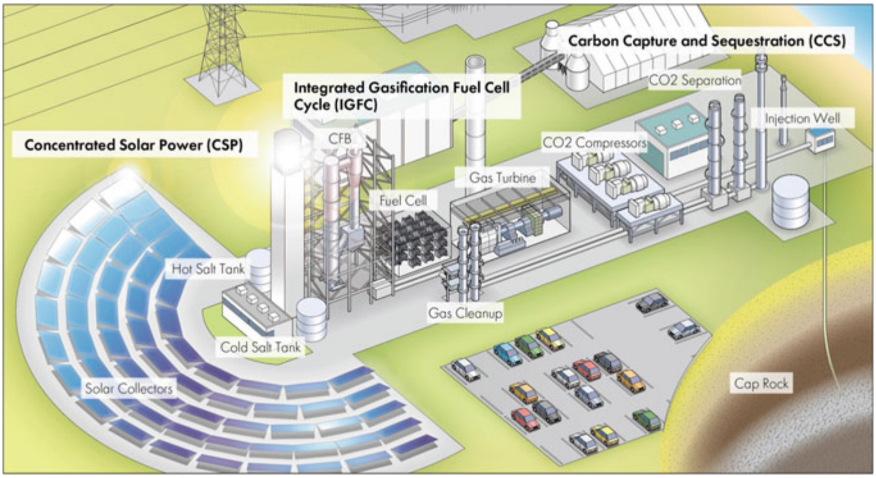

Fig. 24.1 Conceptual design drawing of the solar hybrid BECCS plant

24.3 Plant Design

24.3.1 Plant Configuration

Based on the literature review, the authors conceptually designed a Solar & Biomass Energy Carbon Capture and Sequestration Plant (Solar Hybrid BECCS) for the first time as illustrated in Fig. 24.1.

This design is intended to minimize the R&D element required for the construction by borrowing major components from existing power plants. Specifically, this plant is a combination of three existing plants: a CSP plant, an Integrated Gasification Fuel Cell (IGFC) cycle plant, and a CCS plant. The authors reference published operation data for these plants to ensure the engineering feasibility of the proposed, combined plant.

24.3.2 CSP Plant

The authors reference (Zhang et al. 2013) for the CSP plant. In this design, the solar radiation is collected and focused by collectors, after which the heat is transferred by molten salts at a temperature of 850°C. By using solar concentrator-based heat, the need for partial combustion of the feedstock is eliminated, thus increasing the resultant yield of syngas.

24.3.3 IGFC Plant

Dry wood chips were assumed as the biomass feedstock for the Solar Hybrid BECCS plant for its availability in the market. Based on the operational temperature of CSP, the feedstock characteristics (size, composition, and moisture) and the processing capacities of the biomass gasifiers, the Circulating Fluidized Bed (CFB) gasifier was chosen for the proposed Solar Hybrid BECCS plant. It should be noted that some additional R&Ds are necessary for the gasifier. This is because, while conventional gasifiers utilize the partial combustion (oxy-combustion) of biomass feedstock to generate heat, a CFB gasifier with an external heat supply will be needed for this plant.

For the usage of the product synthetic gas (H2 + CO), the authors assumed an advanced electricity generation cycle called the Integrated Gasification Fuel Cell (IGFC) cycle. This electricity generation cycle first converts the synthetic gas into pure hydrogen + carbon dioxide, then feeds the hydrogen to fuel cells to maximize the generation efficiency. The burnup hydrogen will then be fed to a gas turbine, while the carbon dioxide will be recovered to be sequestered. The waste heat will also be recovered for the steam-turbine electricity generation.

24.3.4 CCS Plant

Among large-scale CCS facilities, the Tomakomai CCS Demonstration Project by Japan CCS Co. Ltd. has been particularly successful in its operation. Due to the similarities in design features, the authors referenced the design of the Tomakomai plant for the design of the CCS facility linked to the Solar Hybrid BECCS plant.

24.4 Method

24.4.1 Environmental Life Cycle Assessment

To estimate the life-time CO_2 removal potential of this newly designed Solar & Biomass Hybrid CCS plant, the authors conducted an environmental Life Cycle Assessment (LCA) in conformity with ISO14040/44.

24.4.2 System Boundary

The product assessed in this LCA is electricity, and as such 1 kWh was chosen as the functional unit. The system boundary of this analysis is cradle-to-gate for electricity.

In other terms, based on the Life Cycle Stage classification by the US DOE (Skone et al. 2016), this LCA includes the LC Stage #1: Raw Material Acquisition (RMA), the LC Stage #2: Raw Material Transport (RMT) and the LC Stage #3: Energy Conversion Facility (ECF).

24.4.3 Database and Software

Ecoinvent 3.5 Cut-off database was used on openLCA version 1.8 software.

24.4.4 Impact Assessment Method

Global Warming Potential (GWP) values as reported in the IPCC 5th Assessment Report were used for the impact assessment. Ecoinvent 3.5 database provides a set of impact assessment methods for IPCC derived GWP as part of the database. However, these default impact assessment methods do not take CO_2 absorption from the atmosphere into account. For this reason, the impact assessment methods for IPCC on Ecoinvent 3.5 are modified so that 1 kg of elementary flow of Carbon Dioxide from the air will cancel 1 kg of elementary flow of Carbon Dioxide emissions to the air. In exchange, "carbon dioxide, biogenic" emissions were modified to be weighted as 1 kg to avoid double counting of carbon removal.

24.4.5 Modeling for Solar Hybrid BECCS

Necessary background data for the plant design and product modeling for the Solar Hybrid BECCS plant were gathered from precedential studies and operational data of existing plants. For the IGFC facility, the reported operational data of Osaki CoolGen power plant were referenced (Ishida 2017; Kenji 2015). Finally, for the CCS facility, reported operational data of the Tomakomai CCS plant (Tanaka et al. 2014) as well as a report published by the U.S. Department of Energy (Skone et al. 2016) were referenced. Assumptions for the primary plant parameters are summarized in Table 24.1.

Table 24.1 Primary Plant Design Parameters

	Symbol	Unit	Baseline value
Electrical output	***Pe***	kW	48,800
Availability factor	***fav***	-	0.43
Lifetime	***LT***	years	40

Table 24.2 Key parameters the product model for 1 kWh electricity production

Input	Amount	Unit
Fuel cell, solid oxide, with micro gas turbine, 180 kW electrical, future	5.4E-9	Items
Synthetic gas from anaerobic gasifier	1.5178	m^3
Flat plate solar collector, Cu absorber	5.8482E-4	m^2
Carbon Capture and Sequestration, construction and O&M	0.48656	kg-CO_2
Electricity generation from syngas, IGFC	0.759069	kg-CO_2

Although this paper does not intend to assume a construction site for future Solar Hybrid BECCS plant, for consistency, data for Northeast Power Coordinating Council (NPCC) region of the U.S. were used throughout in modeling when available.

For the biomass feedstock, the "*wood chips, dry, measured as dry mass*" flow on ecoinvent 3.5 was used without modifications, which includes both the feedstock drying process and the collecting process.

Based on the plant design and assumptions, electricity production was modeled in accordance with the Ecoinvent data quality guidelines. The primary inputs of the model are summarized in Table 24.2. Detailed modeling aspects are not included here.

24.4.6 Modeling for Comparing Power Plants

In order to compare power plants, the following default process models from Ecoinvent 3.5 were adopted without modification: "electricity production, wind, >3 MW turbine, onshore—NPCC, US only" for land-based wind; "electricity production, photovoltaic, 570kWp open ground installation, multi-Si—NPCC, US only" for utility-scale PV; "electricity production, hydro, reservoir, alpine region—NPCC, US only" for hydropower; "electricity production, natural gas, combined cycle power plant—NPCC, US only" for natural gas; "electricity production, hard coal—NPCC, US only" for coal, and; "electricity production, nuclear, pressure water reactor—NPCC, US only" for nuclear.

As Ecoinvent 3.5 does not include an LCI dataset for biomass power plants, these were modeled based on the same assumptions and modeling methods for Biomass & Solar Hybrid BECCS plant. Biomass power plant without CCS was modeled as a combination of Gasification Process Model (without modifications), Fuel Cell + Gas Turbine Model, and Electricity Generation Model; the CCS Process Model was added for the biomass power plant with CCS.

24.5 Results and Discussion

Life cycle inventories for 1 kWh of electricity production were calculated for nine power plants. The GWP (IPCC 2013 Global Warming Potential) indicators for each power plant are illustrated in Fig. 24.2. The estimated life cycle GHG emissions of the electricity production from Solar Hybrid BECCS under our baseline scenario was −0.812 kg CO_2-eq/kWh of electricity production. This calculated net GHG reduction amount of −0.812 kg CO_2-eq per 1 kWh electricity production is a significant improvement over other comparable power plants. Even compared to the conventional BECCS plant, a future power plant, Solar Hybrid BECCS showed a considerably higher carbon removal capability.

The uncertainty was calculated with a Monte-Carlo simulation with 10,000 iterations as Fig. 24.3. Log-normal distrubutions were assumed for the models in Table 24.3.

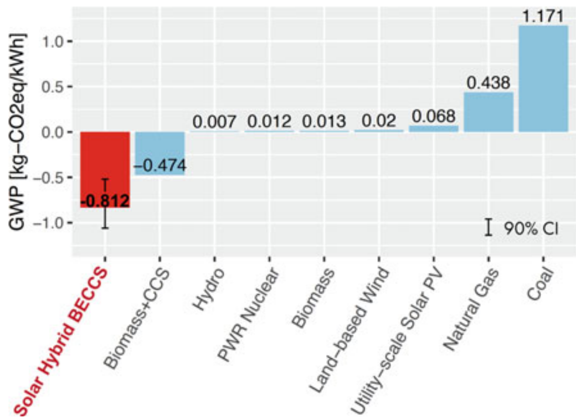

Fig. 24.2 Estimated life cycle GHG emissions of electricity production through solar hybrid BECCS

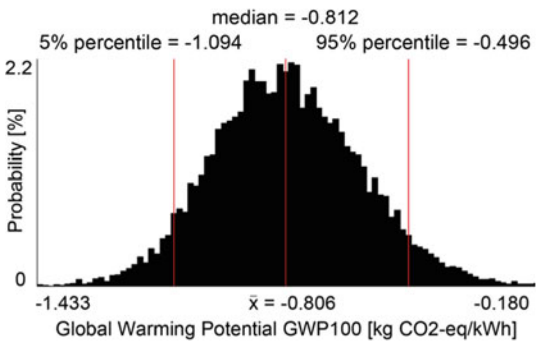

Fig. 24.3 Monte-carlo simulation result for GWP for solar hybrid BECCS

Table 24.3 Assumed geometric standard deviations for the monte-carlo simulation

Input	Geometric SD
SCP, BOP, O&M, Land-use Change and Decommissioning	1.20
Gasification Process, CCS Process	1.10
Fuel Cell + Gas Turbine	1.05

The estimated 90% Confidence Interval of the GWP was from −1.098 to −0.488 kg-CO_2eq/kWh. This means that even at the 95% percentile, net GHG emissions from Solar Hybrid BECCS (−0.496 kg/kwh) is lower than that of a conventional BECCS plant (−0.474 kg/kwh).

This is an encouraging result for Solar Hybrid BECCS, as it indicates that even considering the large uncertainties in plant design, this conceptual plant would outperform conventional BECCS plants.

24.6 Conclusions

This paper proposed and analyzed an innovative sustainable energy option: Solar Hybrid BECCS. The concept is to utilize the heat collected from solar radiation for the pyrolysis of biomass feedstock to generate hydrogen, while recovering and sequestering the carbon emissions from these processes. Such a plant would have a great potential for removing carbon from the air through BECCS, without compromising electrical grid stability. This conceptual plant was designed to minimize the additional R&D elements required towards the construction, and an extensive literature review was conducted to ensure the engineering feasibility of the proposed design.

Environmental impacts of the proposed Solar Hybrid BECCS were analyzed and compared against other power sources through LCA, and the key findings are summarized in Fig. 24.4.

This calculated net GHG reduction amount, −0.812 kg CO_2-eq per kWh of electricity production had the lowest GHG emissions among the nine comparison plants, even lower than conventional BECCS.

One major constraining factor of this conceptual plant is its relatively constricted locations for operation. Because the plant requires good solar radiation as well as access to a stable supply of the biomass feedstock for economical operation, the location availability might be restricted. The authors argue that countries like the U.S. and Spain could potentially offer suitable locations, but there should be other suitable locations in Southeast Asia as well, where the biomass supply is abumdant.

In conclusion, this technologically feasible energy option may have great potential toward achieving energy sustainability, contributing to both the under 1.5 and under 2-degree increase scenarios. Our LCA results indicated that this plant could achieve

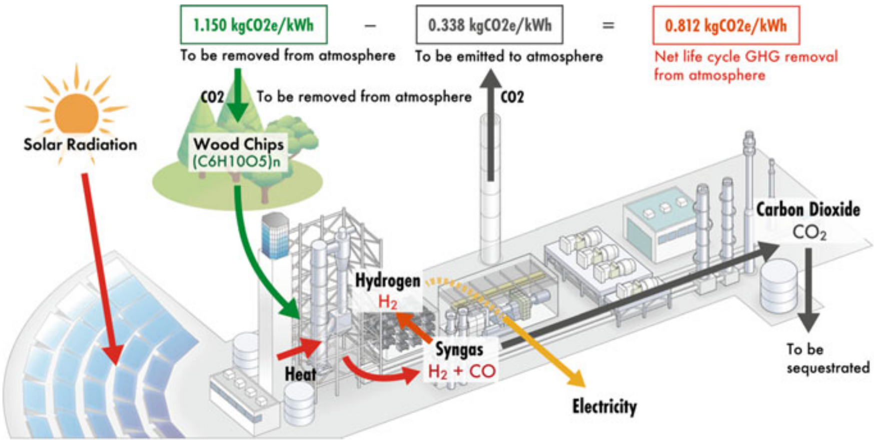

Fig. 24.4 Calculated elementary flows of solar hybrid BECCS plant

carbon removal with the sun and the forest, two fundamental gifts from nature. In answering the question "is a Solar Hybrid BECCS plant a promising option toward designing a sustainable future energy system?" We conclude that the answer is yes.

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Chapter 25
Environmental and Economic Impacts of Biofouling on Marine and Coastal Heat Exchangers

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Abstract Biofouling is a major problem that affects the heat transfer efficiency of marine and coastal heat exchangers. The reduced heat exchanger efficiency results in energy loss and thereby affects the overall energy efficiency in the marine industry segment. Additional energy is required to compensate for the energy loss leading to increased fuel consumption which in turn contributes to global environmental issues like climate change. The current industrial methods of biofouling mitigation or removal from heat exchanger surfaces increase both operational and maintenance expenditure causing further environmental damages. This paper presents two models to provide an overview of the major environmental and economic impacts due to biofouling in marine heat exchangers. The study results suggest the need for sustainable biofouling prevention techniques to improve the energy and resource efficiency of marine heat exchangers.

Keywords Biofouling · Heat exchanger · Energy efficiency · Resource efficiency · Environmental impacts

25.1 Introduction

In the twenty-first century, society faces a lot of environmental issues. Of particular concern is the climate-related issues which are predominantly caused by industrialization. Industrial development has made our lives more comfortable, but it has also caused a huge demand in the energy requirement. For the past century, this energy demand has been mainly satisfied through the combustion of fossil fuels,

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which resulted in the increased emission of greenhouse gases. This has led to global warming and climate change. The effects of climate change are already visible in the form of floods, hurricanes, drought, heatwaves, melting of polar icescapes, and rise in the seawater levels, among others (Bott 2006). On the other hand, with the current technology improvements, it is evident that the demand for energy will not decline but will be increasing every year. Therefore, it is important to improve the energy efficiency of our industrial processes to reduce the environmental impact.

The marine industry segment has a lot of industrial processes associated with energy transfer. It is significant to have energy efficient devices in these processes. Heat exchangers are widely used for heat transfer or energy transfer applications in the marine industry. Marine heat exchangers are mainly installed and operated in offshore industries like oil refineries, desalination plants, power generation and chemical plants (Malayeri et al. 2015). The efficiency loss in these heat exchanger devices will thereby have a significant effect on the energy utilization in the marine industry segment.

Biofouling of marine heat exchangers is an issue faced by offshore industries all over the world. In the marine industry, biofouling could be described as the undesirable accumulation of deposits (biotic) on equipment surfaces by adhesion, growth and reproduction (Cao et al. 2011; Callow and Callow 2011). Marine biofouling on heat exchangers can be classified into microfouling (fouling due to microscopic organisms like bacteria and diatoms) or macrofouling (fouling due to macroorganisms like barnacles, oysters, mussels, polychaete worms, bryozoans and seaweed) (Cao et al. 2011; Callow and Callow 2011). Biofouling is generally more severe in areas where the water temperature is high because it provides the ideal condition for breeding and growth of biofouling organisms (Ratel et al. 2013). The intensity of marine biofouling in heat exchanger surface depends on several factors like the process fluid, exchange type and geometry, operating conditions, among others (Ratel et al. 2013).

The high importance of the heat exchanger equipment in the marine industrial applications intensify the criticality of the biofouling problem. Biofouling mainly affects the heat transfer efficiency of the heat exchanger equipment, which leads to energy loss (Hansen 2018). This additional energy requirement is mostly fulfilled by fossil fuel combustion and contributes to more emission of greenhouse gases (Bott 2006). Numerous studies have estimated that heat exchanger fouling leads to additional costs in the order of 0.25% of the gross domestic product (GDP) of industrialized countries (Malayeri et al. 2015; Müller-Steinhagen et al. 2011). Thus the biofouling of heat exchangers not only compromises the environmental welfare but also leads to significant economic losses (Costa et al. 2011).

25.2 Methodology

In this paper, a research study is conducted to find out the main environmental and economic impacts due to biofouling in marine and coastal heat exchangers. The research study was performed as part of the joint project between the Chalmers University of Technology, JOIN Business & Technology AB, Electrical Pipe for Fluid Transport AB (EPFF), and Alfa Laval Corporate AB. The study consisted of a literature review and interviews with different stakeholders in the project. Quantitative assessments of the environmental and economic impacts were not included in the study.

The material for the literature study was gathered by using databases like Scopus, Science Direct, Web of Science, and Google Scholar. The literature mainly consists of papers from both journals and conferences. There was no specific year limit used in the selection process. For a quick determination of whether a paper is relevant for the study or not, title, abstract, introduction, and conclusion were studied. To find more interesting publications, references of references were tracked. All the quantitative information provided in the report has been gathered from various articles used in the literature study.

Semi-structured interviews were conducted with heat exchanger product experts. The interviews helped to understand the problems associated with biofouling prevention from an economic perspective as well as from an environmental perspective. A qualitative analysis of the information gathered from both the literature study and the interviews were done to identify the main issues associated with biofouling in marine and coastal heat exchangers.

25.3 Results

From the literature study and the interviews conducted, the major environmental and economic impacts due to biofouling in marine and coastal heat exchangers were identified. The environmental impacts are presented in Sect. 3.1 and the economic impacts in Sect. 3.2.

25.3.1 Environmental Impacts

This section describes the main environmental impacts due to biofouling in marine and coastal heat exchangers. The impacts are classified into three categories. A cumulative model of environmental impacts is presented in Fig. 25.1.

Category 1: Biofouling and the subsequent rise in global warming potential

A major issue associated with heat exchangers due to marine biofouling is the reduced heat transfer efficiency (Hansen 2018; Trueba et al. 2015). The fouling matter sticks on to the heat exchanger surface and reduces the efficiency of the heat exchanger to either transmit or absorb heat (Trueba et al. 2015). Considerable energy loss occurs due to reduced heat transfer at the heat exchanger surface (Kronholm 2018; Bertilsson 2018). The case study article ‘The Heat Transfer Resistance of Various

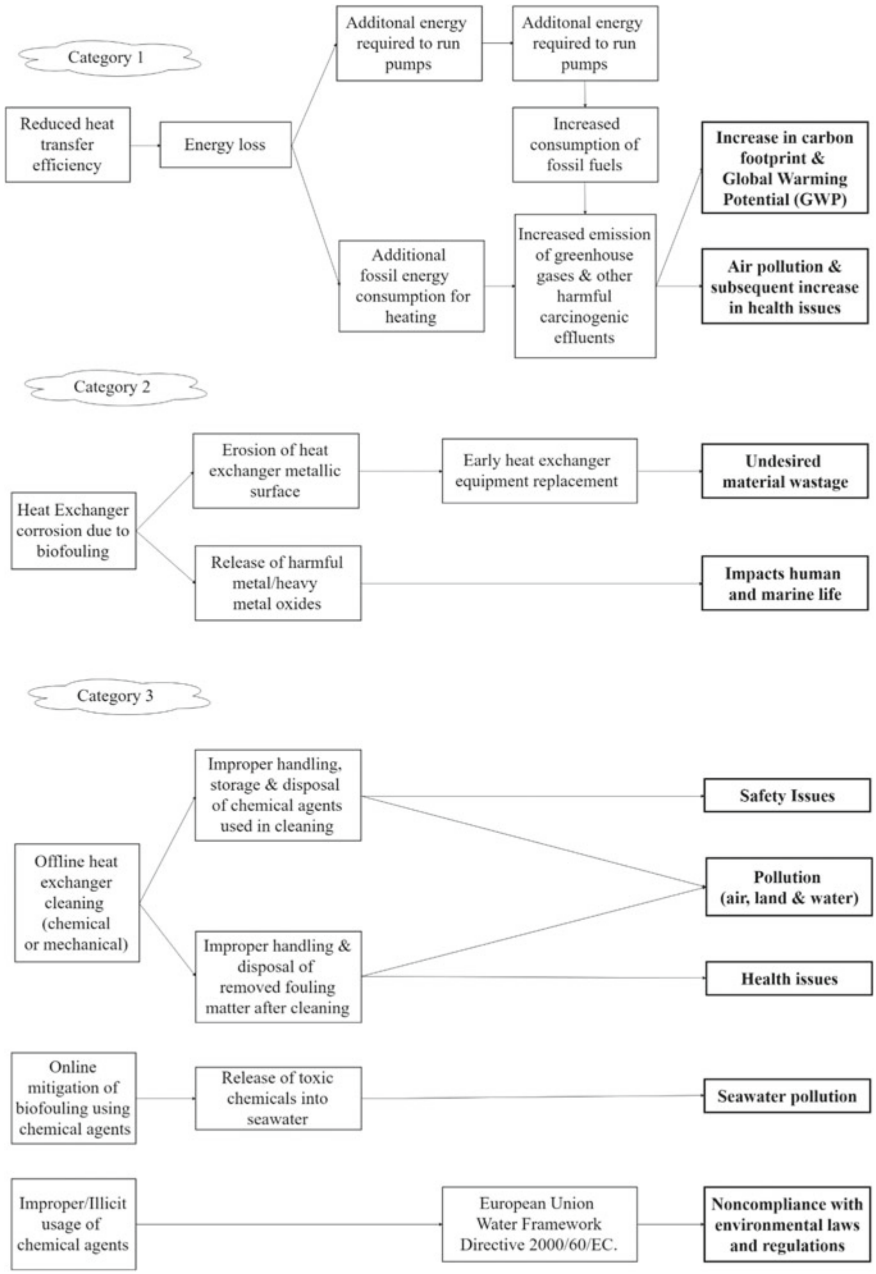

Fig. 25.1 Cumulative model of environmental impacts

Heat Exchanger Tubing Alloys in Natural and Synthetic Seawaters' published by Sheldon et al. in 1984 evaluates the impact of fouling on heat transfer efficiency of a condenser using tubing material Type 439 Stainless Steel (T439SS) (Sheldon and Polan 1984). The case study shows that one month of exposure to a biofouling environment reduced the heat transfer efficiency of the condenser by 19% (Sheldon and Polan 1984). Six months exposure of the same condenser in an inorganic depositing environment (calcareous or slit) only caused 9% reduction (Sheldon and Polan 1984). Thus biofouling could increase the heat transfer resistance to a greater degree in a much shorter time when compared to inorganic deposits (Sheldon and Polan 1984).

Therefore, to compensate for this energy loss at the heat exchanger surface, additional energy has to be supplied. In most cases, fossil fuels are the main energy source of heat exchangers that are used for heating purposes. Thus marine biofouling will directly result in additional consumption of fossil fuels (Casanueva-Robles and Bott 2005). More and more consumption of fossil fuels will increase the emission of air pollutants like CO_2, SO_2 & NO_X and thereby a subsequent rise in the global warming potential (GWP). The case study article 'The Environmental Effect of Heat Exchanger Fouling' published by Müller-Steinhagen et al. in 2005 proves that there is a direct relationship between the biofilm thickness on the heat exchanger surface and the overall CO_2 emissions in seawater cooled power plants (Casanueva-Robles and Bott 2005). A 550 MW coal-fired power station was considered for the case study (Casanueva-Robles and Bott 2005). In the power station, steam is condensed in seawater cooled high and low pressure condensers (Casanueva-Robles and Bott 2005). The steam is condensed in order to reduce the steam pressure, which will help to increase the pressure driving force across the turbines (Casanueva-Robles and Bott 2005). The biofouling affected the proper functioning of the condensers and increased the steam pressure, which resulted in the reduction of driving force across the turbines (Casanueva-Robles and Bott 2005). This resulted in subsequent energy loss and affected the plant's efficiency (Casanueva-Robles and Bott 2005). To compensate for this energy loss, more steam has to be produced and this caused more CO_2 emissions (Casanueva-Robles and Bott 2005). The CO_2 emissions were compared to different values of biofilm thickness on the condenser surface (Casanueva-Robles and Bott 2005). For both high and low pressure condensers, the biofilm thickness was considered from 0 to 10^3 μm (Casanueva-Robles and Bott 2005). The percentage increase in CO_2 discharge was 0.75% for low pressure condenser and 0.69% for high pressure condenser (Casanueva-Robles and Bott 2005). Thus for the thickest biofilm studied (10^3 μm), the total additional CO_2 produced was 6.2 tonnes per hour (Casanueva-Robles and Bott 2005). The case study concluded a significant proportional increase in power plant's overall CO_2 discharge with an increase in biofilm thickness on the condenser surfaces (Casanueva-Robles and Bott 2005).

Another example regarding CO_2 emissions caused by heat exchanger fouling is provided in the article 'Heat Exchanger Fouling: Environmental Impacts' published by Müller-Steinhagen et al. in 2011 (Müller-Steinhagen et al. 2009). In the article, the authors provide an approximate estimation of the overall annual CO_2 emissions caused by heat exchanger fouling in the oil refinery operations. To heat the crude oil, the oil refineries generally rely on a battery of shell & tube heat exchangers also called a crude preheat train (CPT) (Müller-Steinhagen et al. 2009). The decreased efficiency of these heat exchangers due to fouling is estimated to have a 10% increase in fuel usage (Müller-Steinhagen et al. 2009). The article states that, at a global scale, this corresponds to approximately 88 million tons per annum of CO_2 emissions in the oil refinery operations alone (Müller-Steinhagen et al. 2009).

In the case of marine heat exchangers that are used for cooling purposes, seawater is mainly used to absorb the excess heat generated. Biofouling causes the narrowing of the flow area and thereby result in reduced water flow or a pressure drop inside the heat exchanger (Kronholm 2018; Bertilsson 2018; Radicone 2009). This will also result in reduced heat transfer and energy loss. In order to compensate for the reduced heat transfer, more seawater has to be pumped. This will directly result in additional water consumption. Apart from that, the water pump consumes additional energy (electrical energy) to supply more seawater (Hansen 2018; Kronholm 2018). In most cases, electrical energy utilized for running the pumps is obtained through the burning of fossil fuels (Hansen 2018; Kronholm 2018). This will also increase CO_2 emissions and thereby an equivalent rise in the global warming potential.

Several other scientific studies and conferences like 'Heat Exchanger Fouling and Cleaning X—2013' & 'Heat Exchanger Fouling and Cleaning XI—2015' estimated that the heat exchanger fouling is responsible for 1 to 2.5% of overall global CO_2 emissions (Malayeri et al. 2015; Müller-Steinhagen et al. 2009, 2011). However, it is highly difficult to attain a cumulative value on the overall percentage of CO_2 emissions due to biofouling. This is because, the values will always vary according to factors like the severity of fouling, heat exchanger operating conditions, plant energy source and so forth (Müller-Steinhagen et al. 2009). Apart from that, the global energy consumption rate by the offshore industries is not declining but increasing every year. Therefore, the actual percentage of CO_2 emissions due to heat exchanger fouling could be much higher in reality.

Category 2: Heat Exchanger corrosion and environmental issues

Another major issue with marine biofouling is the corrosion that happens on the heat exchanger surface (Hansen 2018). The deposition of biofilms (either micro fouling or macro fouling) will lead to the development of special chemical environments that speeds up corrosion of heat exchanger metallic surface. If such biofouling is left unchecked, it will eventually result in material erosion on the heat exchanger surface and causes leaks, which requires effective maintenance and repairs. Frequent maintenance and repairs will reduce the equipment's operational lifetime and lead to early scrapping/disposal of the product. Common heat exchanger materials are Titanium, Stainless Steel, Stainless Steel alloys, Copper alloys, Aluminium alloys, among others (Hjalmars 2014; Michels et al. 1979; Darby 1984; Kapranos and Priestner 1987). Thus biofouling corrosion leads to undesired material wastage. Moreover, in the case of corrosion, metal or heavy metal oxides could be also released to the atmosphere as by-products of fouling (Müller-Steinhagen et al. 2009). This could cause serious health issues that affect human and animal welfare (Müller-Steinhagen et al. 2009).

Category 3: Environmental issues associated with the process of biofouling mitigation or removal

Currently, there are many technologies employed in the industry for the prevention or the mitigation of biofouling in marine heat exchangers. The companies use online biofouling prevention techniques, offline biofouling prevention techniques or a combination of both (Müller-Steinhagen et al. 2011). The technique that will be adopted depends on several factors like the type of heat exchanger, type of fouling, severity of the fouling, cost and expenses related to the biofouling prevention technique, plant operational characteristics, the production capacity of the plant, seawater conditions, environmental regulations, climate conditions of the region where the heat exchanger is functioning and so forth. (Müller-Steinhagen et al. 2011). In the case of online techniques, the cleaning or removal of biofouling from heat exchanger surfaces is done without removing the heat exchanger from its current operation (Müller-Steinhagen et al. 2011). But in offline cleaning, heat exchangers have to be moved out of the current operation (Müller-Steinhagen et al. 2011).

A widely used online technique for the mitigation of marine biofouling in the industry is the application of chemical agents like biocides, antiscalants or antifouling agents (Kronholm 2018;Müller-Steinhagen et al. 2009). The dosage of these chemicals mainly depends on the type and the severity of fouling. These chemical agents can reduce the growth and deposition of biofoulants on heat exchanger surfaces. But, at the same time, they contain considerable amounts of chemicals like chlorine, polyphosphate, hypochlorite, coagulants bromine, zinc, among others (Kazi 2012). If the application process of chemical agents is not properly monitored, it could result in the release of chemicals to seawater. This leads to seawater pollution and affects marine life. It also leads to the violation of important environmental legislation such as Water Framework Directive 60/2000/EC of the European Union (Müller-Steinhagen et al. 2009, 2011).

A popular offline cleaning technique is the mechanical cleaning of heat exchangers using manual labour and chemicals. The removed fouling matter after the cleaning process could contain harmful bacteria, fungi, carcinogenic/radioactive matter & other microbial particles (Müller-Steinhagen et al. 2009). Improper disposal of these ‘removed fouling matter’ as well as the ‘toxic chemicals used in the cleaning process’ cause severe environmental pollution and health issues (Müller-Steinhagen et al. 2009). For example, the removed fouling matter could have the presence of Legionella (a pathogenic group of Gram-negative bacteria) (Bott 2006; Flemming 2002). Biofilms are known sources of Legionella pneumophila which causes a pneumonia-type illness called Legionellosis (Abdel-Nour et al. 2013). In addition to that, the inappropriate handling of chemicals while usage also results in safety issues (for example, burns) due to exposure to chemicals (Müller-Steinhagen et al. 2011).

The research study provides clear evidence that biofouling in marine and coastal heat exchangers lead to severe environmental, climate as well as health issues.

25.3.2 Economic Impacts

This section describes the major economic impacts due to biofouling in marine and coastal heat exchangers. The impacts are classified into four categories. A cumulative model of the economic impacts is presented in Fig. 25.2.

Category 4: Reduced heat exchanger efficiency and subsequent costs

From an economic perspective, the biggest problem caused by marine heat exchanger biofouling is the loss in production due to the reduction in heat transfer efficiency. For big industries like refineries and petrochemical plants, energy loss due to reduced heat transfer could result in a subsequent loss in their overall production. Additional energy has to be supplied to compensate for the energy loss. Fossil fuels are the commonly used energy source and with the increase in biofouling, the consumption of fossil fuels also increases. This will increase production costs (Hansen 2018).

To avoid these production losses and the costs associated with that, the heat exchanger users will try to increase the flow inside the heat exchanger. To increase the flow, higher capacity pumps have to be installed. This causes an increase in pump purchasing costs (Hansen 2018; Kronholm 2018). The increase in the pump cost is highly variable depending on the severity of biofouling in each case (Hansen 2018). Hence, it is difficult to provide an average range of values (Hansen 2018). The higher capacity pumps will result in high energy consumption (Kronholm 2018). As a result, the energy costs (mostly electrical energy) will also become higher with the increase in biofouling (Kronholm 2018). Thus resulting in a significant increase in the overall operational expenditure.

Category 5: Biofouling corrosion and subsequent costs

If the biofouling deposits formed on the heat exchanger surfaces are not timely removed, the fouling deposits will erode the surface. This affects the proper functioning of the heat exchanger and further decreases the heat exchanger life expectancy. Therefore, if left unchecked, biofouling will result in early heat exchanger replacement costs (Hansen 2018; Kronholm 2018; Bertilsson 2018). Further, biofouling corrosion will lead to leaks and call for unscheduled repair or maintenance. This will not only increase the maintenance expenditure for the end-user but also increase the operational expenditure due to unscheduled equipment downtime and subsequent loss of production (Hansen 2018). Frequent repair and maintenance of the heat exchanger will also reduce the equipment life and thereby leads to increased depreciation costs.

Category 6: Biofouling removal or mitigation costs

Therefore, to reduce the production loss and the additional operational & maintenance expenditure, the heat exchanger users will try to remove biofouling from the heat exchanger surface. There are both online and offline biofouling prevention techniques. Accordingly, there are various costs associated with these techniques.

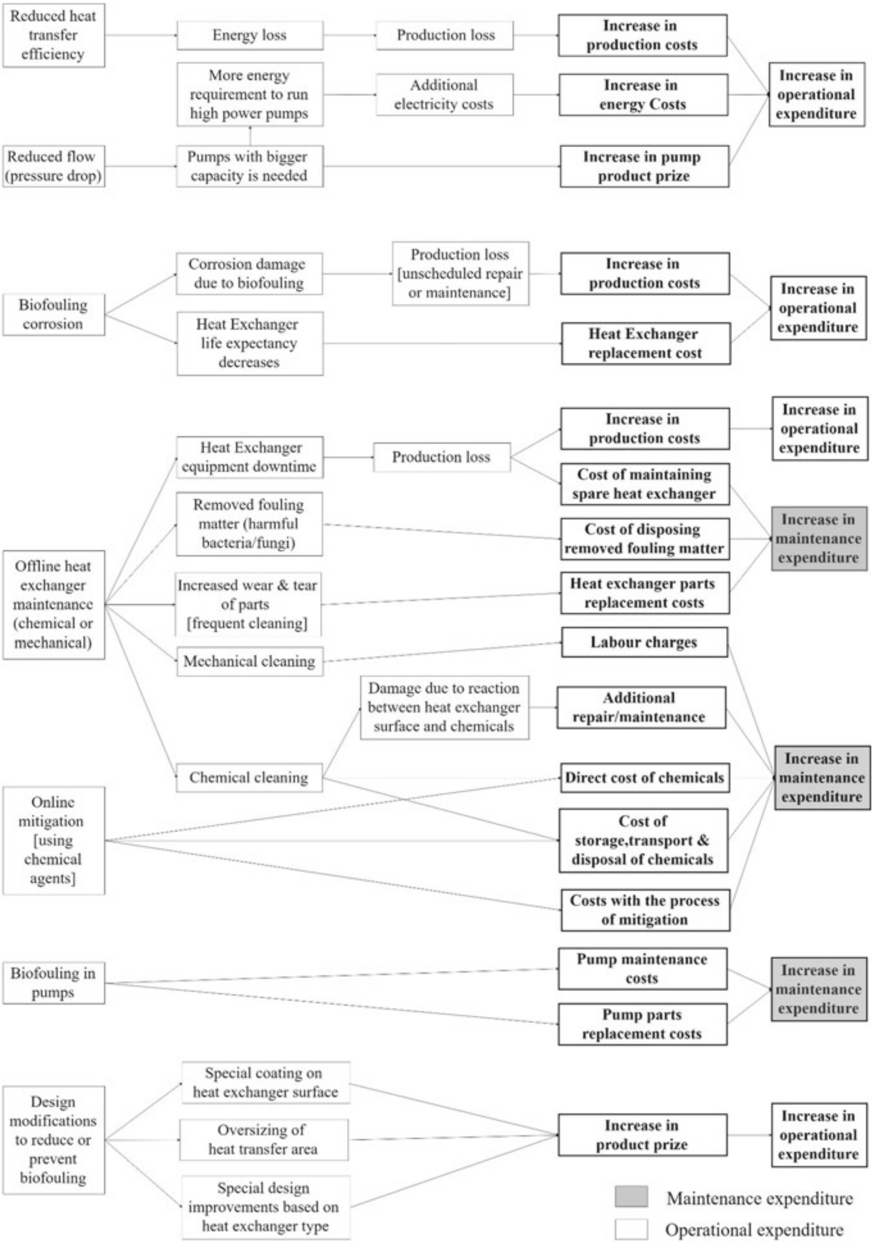

Fig. 25.2 Cumulative model of economic impacts

The main cost associated with online biofouling prevention is the direct cost of the chemicals that are used for the removal of deposits from time to time (Hansen 2018; Kronholm 2018; Bertilsson 2018). Then there are costs associated with the process of mitigation based on the mitigation techniques used. Due to strict environmental regulations, the storage, transportation and the proper disposal costs (treatment costs) of the chemicals used in the mitigation process become a significant factor in the overall costs associated with biofouling prevention (Hansen 2018). These costs are directly dependant on the rate of biofouling in each case. As the biofouling rate is a variable factor, it is difficult to provide an average range of values (Hansen 2018).

Biofouling causes the requirement of periodic offline cleaning of heat exchanger surfaces (Müller-Steinhagen et al. 2011). The cleaning schedules vary widely and depend mainly on the rate of biofouling which in turn depends on local characteristics like the plant operating conditions, physical and chemical properties of the process fluid, heat exchanger material properties, and so on (Michels et al. 1979). For example, some heat exchangers are cleaned daily, and some others weekly, monthly or even annually (Michels et al. 1979). In offline cleaning, the heat exchangers have to be removed from the operation and then disassembled (Hansen 2018). A popular cleaning technique is the mechanical cleaning of heat exchanger surfaces by employing manual labour (Hansen 2018; Chambon et al. 2017). The main cost associated with offline mechanical cleaning is labour charges (Hansen 2018; Kronholm 2018; Bertilsson 2018; Kazi 2012). Offline cleaning is also performed using chemicals (Kazi 2012). A major disadvantage with offline chemical cleaning is the potential for corrosion damage due to undesired reactions between heat exchanger surface and the chemical used (Kazi 2012). This would cause additional repair costs (maintenance expenditure) or even an early replacement of the heat exchanger if the corrosion effects are irreparable (Hansen 2018). There is also the direct cost of the chemicals used in the cleaning process. Further, as mentioned earlier in this section, the storage, transportation and proper disposal costs of the chemicals used in the cleaning process, also contribute to the total costs in the offline chemical cleaning process.

Offline biofouling cleaning techniques will cause significant equipment downtime as the heat exchangers are removed from the current operation. Thus there are also production losses associated with offline biofouling prevention. To prevent these production losses, usually, a spare heat exchanger will be maintained. So, there is also the additional cost of maintaining a spare heat exchanger. The pumps that are used to supply seawater to the heat exchangers are also subjected to marine biofouling. Thus biofouling will also result in additional pump maintenance costs or pump cleaning costs for the end-user (6). Apart from that, the frequent cleaning of heat exchangers and pumps to remove the deposits will cause wear and tear of heat exchanger parts and pump parts. This will decrease the life expectancy of parts and results in the increase of parts replacement costs and overall maintenance expenditure for the end-user.

Category 7: Heat exchanger design modifications due to biofouling

As biofouling is a major unresolved problem to the heat exchanger end-users, the heat exchanger manufacturing companies try to improve the heat exchanger resistance towards biofouling by improving their product design.

A generally referenced source for deciding fouling factors during the design of heat exchangers is TEMA (The Tubular Exchanger Manufacturers Association) (Diaz-Bejarano et al. 2017; Ross et al. 2015). One common method followed is to increase or oversize the heat exchanger heat transfer area to account for diminished performance due to biofouling (Diaz-Bejarano et al. 2017; Ross et al. 2015).

Design modifications are also done based on the type of heat exchanger. For example, for a shell and tube heat exchanger, a common solution is to increase the heat exchanger tube side velocities (Coletti et al. 2015). This increases the wall shear stress, and thereby less fouling material is deposited on tube surfaces (Coletti et al. 2015). In the same way, to prevent biofouling in a plate heat exchanger, one might undersize the unit to keep the turbulence high in the heat transfer channels.

Another common practice is to add effective surface coatings to mitigate biofouling related issues in marine heat exchangers (Santos et al. 2017). Silicone-based coatings and Polymer coatings based on the sol-gel process are widely used to resist fouling (Hjalmars 2014). More advanced fouling resistant coatings like Carbon nanotube-polytetrafluoroethylene, Nano-hybrid sol-gel coatings, Diamond-like carbon (DLC) coatings, among others, are formulated through research and development (Hjalmars 2014). All these design alterations will help to reduce biofouling, but will also increase the heat exchanger product cost in the market.

25.4 Discussion

The global energy requirement is increasing year by year. As heat exchangers are one of the most efficient means of heat transfer, the heat exchanger market is also growing, and the increase in the number of heat exchangers will cause a proportional increase in the environmental and economic impacts associated with heat exchanger biofouling. Thus, it is necessary to implement effective methods to reduce biofouling. Currently, there are various techniques adopted for biofouling prevention in marine heat exchangers. Primarily, the heat exchanger manufacturers would prefer to mitigate biofouling through the proper design of heat exchangers and then, the most adopted method is the use of online mitigation techniques (Müller-Steinhagen et al. 2011). Online methods are more preferred when compared to offline techniques as it will not affect the equipment availability.

Among different online mitigation techniques, the most common method is the use of chemical agents (Müller-Steinhagen et al. 2009). But, the presence of toxic substances in these chemical agents could greatly outweigh, from an environmental point of view, the benefits of fouling mitigation. Hence, it is significant to adopt more sustainable online biofouling mitigation techniques. Other online biofouling mitigation techniques include physical and mechanical methods. These methods do not involve the usage of chemical agents, but their applicability is limited and depends on various factors like the type and geometry of the heat exchanger, intensity of the fouling, operations conditions and so on (Müller-Steinhagen et al. 2011). Some examples of online mechanical methods consist of the usage of different cleaning projectiles (for example, sponge balls, and wire brushes) and tube inserts (for example, twisted tapes, coils, and wire matrix inserts) (Müller-Steinhagen et al. 2011). The examples of physical methods of online biofouling mitigation include the application of electric fields, sonic technologies, magnetic fields, ultraviolet light, and surface modifications using surface coatings (Trueba et al. 2015). Several quantitative efforts are currently ongoing to further develop and improve the online biofouling mitigation techniques so that they are more environment-friendly and at the same time economical. The successful implementation of such green initiatives in the market requires the combined and collaborative efforts of researchers, heat equipment manufacturing companies and also heat exchanger users [offshore industries].

25.5 Conclusion

The results from the literature review and the qualitative interviews conducted show that heat exchanger biofouling contributes to major environmental issues like global warming and climate change. From an economic perspective, marine biofouling increases both operational expenditure and maintenance expenditure in offshore industrial processes. Although the use of chemical agents is effective in fouling mitigation, it affects marine life and also causes significant health and safety issues to humans through air, land and water pollution. Hence, this paper highlights the need to develop and adopt new solutions for biofouling prevention in heat exchangers that are eco-friendly but at the same cost-effective. Further research, both qualitative & quantitative is needed to identify such sustainable biofouling prevention techniques, their effectiveness in preventing biofouling, and how these techniques could be introduced in the heat exchanger industry.

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Chapter 26
Ecological Cost-Benefit Analysis of a Sensor-Based Parking Prediction Service

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Abstract The fast-growing sector of smart city applications resulting from the ongoing digitalization has a huge impact on our society. They use innovative technologies to improve for example mobility, optimize shopping or offer intelligent travel guide assistance. However, these applications have not only the potential to benefit our daily life with precisely targeted services, but also to reduce the environmental impact we create. In this paper the authors present the proceeding for a simplified life cycle assessment on the special case of a sensor-based parking prediction service of the Deutsche Telekom called "Park&Joy".

Keywords Life cycle assessment · Emission · Smart city · Sensor · Parking

26.1 Introduction

In 2018, Deutsche Telekom began the rollout of a new service offering. They implemented a new Smart City application in cooperation with various technology companies with the aim of relieving traffic in German city centers. This application, in the form of a navigation app in combination with a parking lot search function and an integrated ticket booking system, has the goal of massively reducing parking traffic emissions. Within this investigation these parking traffic emissions is estimated 140,000t CO_2 eq per year for Germany's 80 largest cities in total.

It aims to reduce the time spent searching for parking lots significantly by displaying possible unoccupied parking lots in the target area to a user of the mobile application and guiding him through the traffic accordingly. The availability of unoccupied parking lots is a purely statistically determined and computer-aided value

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calculated from complex data on the traffic volume, the day of the week, the time of day and other information relevant for forecasting. Sensors embedded in the asphalt randomly determine whether the occupation status of the parking lots above and thus sharpen the probability forecast.

With a comprehensive usage of the “Park&Joy” system, a significant reduction of the environmental impact of individual traffic in inner cities is feasible. On behalf of Deutsche Telkom, Fraunhofer IZM has developed a methodical approach to evaluate this potential.

26.2 System Architecture of “Park&Joy”

The navigation application “Park&Joy”, which is available for Apple and Android devices, consists of two architectural elements on the hardware perspective. For the detection of vehicles, sensors embedded directly in the road asphalt are used. These sensors connected to various server systems provide the communication and predication functions. As a basis for the ecological cost-benefit analyses, a detailed examination of these two main architectural elements is necessary.

26.2.1 Sensor Composition

Fraunhofer IZM dismantled one of those sensors and thus recording the dimensions, weights and materials used for the sensor components. This disassembly carried an assessment of the sensor’s longevity, reparability and recyclability in addition to the life cycle analysis.

Each step of the dismantling process is recorded in a protocol including the used tools, the type of connection, the time required and any damage that may have occurred during dismantling, for valuation and further possible assessments. The external dimensions of the sensor are 75 mm x 72 mm with a total weight of 291 g. This total weight distributed among the concrete components as shown in Table 26.1.

A particular challenge during dismantling is the almost exclusive use of adhesives for fixing the individual components. The reason of this robust construction is the operating location of the sensors. Directly inserted into the road with the aid of a core borehole and sealed with polyurethane, they remain in the street section until the end of their lifetime. Therefore, the sensors have to withstand various weather conditions and the weight of diverse vehicles, which makes an IP68-certification inevitable.

The “Park&Joy” sensor primarily detects parking vehicles with an integrated infrared sensor. In case of a malfunction or disruption an additional magnetic field sensor will take over this task. These two detection elements and one antenna placed on the upwards pointed secondary board are connected with the primary board. However, a lithium thionyl chloride battery at 13,000 mAh (3,6 V) powers the primary board, which is containing the SIM card slot and the NB-IoT module (LTE band 8 at

Table 26.1 Sensor components including weight

Component	Weight (g)
Battery	96.36
Foam pads	3.59
Copper coil	0.69
Battery holder	27.06
Cable	0.97
Plastic seperator	26.75
Secondary board	9.82
Primary board	16.63
Outer shell	106.15
SIM card	0.08
Total	288.10

900 MHz and band 20 at 800 MHz), as well as all active and passive components to ensure all sensor functions (U-blox Holding 2018). All sensor elements are enclosed in a welded polyethylene chassis (Fig. 26.1).

In order to provide the most accurate possible characterization of the sensor's assembly and connection technology elements as well as avoiding further disassembly of the NB-IoT module, a computer tomography image (CT) of the printed circuit board was taken (Fig. 26.2). This CT-image provide precise determination of die-areas and dimension measurements of the remaining active and passive components of the primary board. Because of the exclusive use of adhesives and solder points, a non-destructive disassembly of the whole sensor is not possible (Table 26.2).

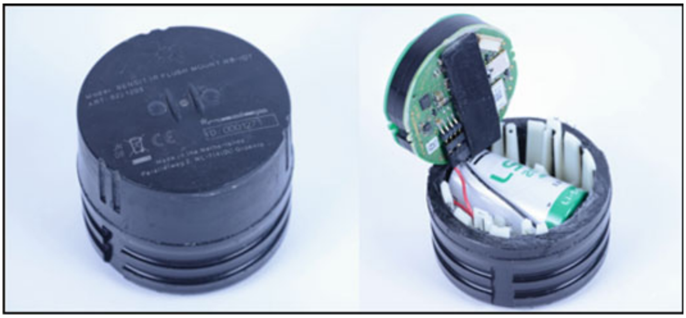

Fig. 26.1 Parking sensor closed (left) and open (right)

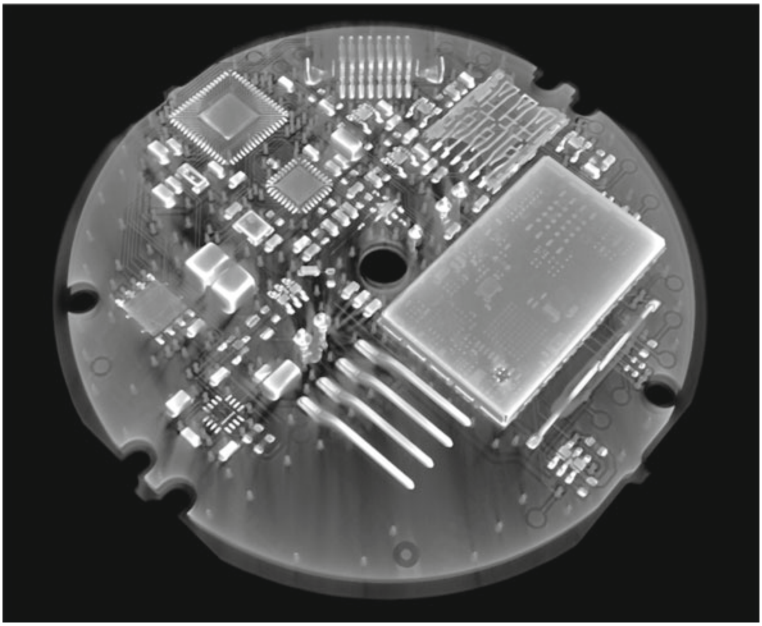

Fig. 26.2 Computed tomography scan of the primary board

Table 26.2 Vehicle population by fuel type in Germany (Federal Motor Transport Authority Germany 2018b)

Fuel type	Number	Share (%)
Petrol	30,451,268	65,5
Diesel	15,225,296	32,8
Liquid gas (LPG)	421,283	0,9
Hybrid	236,710	0,5
Natural gas (CNG)	75,459	0,2
Electric	53,861	0,1
Other	10,717	0,0
Total	46,474,594	100

26.2.2 Server Infrastructure

The sensors are equipped with SIM cards from Deutsche Telekom and use the public telecommunication network to connect the backend systems. These backend systems consist of the parking prediction servers, the app's application server, various interfaces and external data source connections. In total the present architecture model for "Park&Joy" use 10.6 Servers for all system relevant tasks, for example navigation, prediction, device management, monitoring or payment processing. Due to the only partial use of certain servers reasoned by the degree of virtualization and usage of

Table 26.3 GWP Server

	Value	Unit
Number of servers	10.60	pcs
Server lifetime	4.00	a
GWP manufacture	300.00	$kgCO_2eq$
Power consumption	180.00	W
PUE	1.50	
Energy demand	2366.82	kWh
Electricity mix	0.49	$kgCO_2eq/kWh$
GWP Server usage per year	1157.37	$kgCO_2eq/a$
Use of all servers per year	12,268.17	$kgCO_2eq/a$

colocation compute center, the specifications of the servers for the system architecture model is not exactly determinable. However, the lack of information concerning for example installed HVAC (heating, ventilation and air conditioning) or type and size of data storage leads to apply a dataset for a generic server configuration (Berwald et al. 2015).

This configuration is specified by 8 cores and 8 GB of RAM for each server and no additional graphic cards or peripheral units and an operation time of 24 h a day and 365.25 days per year. This decision is based on the procedure to create a quick calculation with readily accessible values from literature and the subsequently multiplication of these values to simulate possible additional burden from the server infrastructure. Following this approach an estimation of the actual influence of the server systems with respect to the overall emissions can first be created and then subsequently carried out by a comparison of the data situation with real data after a complete rollout (Table 26.3).

26.3 Basic Environmental Data

For the ecological cost-benefit analysis, the emissions for manufacture and operation of the sensor and server systems are compared with the emissions saved by low driving kilometers during the search for a parking lot. Therefore, the saved emissions as the main functional unit is significantly influenced by various factors:

- Sensor lifetime
- Server lifetime
- Number of covered parking lots per sensor
- Number of daily parking operations per parking lot.

The environmental assessment in this paper does not consider the necessary telecommunication infrastructure (e.g. base stations, radio network controller, routers), in behalf of a data transfer volume of around 3.66 MB per year and sensor.

Table 26.4 Probability model of parking attempt

		"Park&Joy" with sensors (%)	"Park&Joy" without sensors (%)	Without "Park&Joy" (%)		
Driving distance parking attempt (m)	500	96	78	50	33	25
Parking attempt	1	96.0	17.2	50.0	33.0	25.0
Parking attempt	2	3.8	3.8	25.0	22.1	18.8
Parking attempt	3	0.2	0.8	12.5	14.8	14.1
Parking attempt	4	0.0	0.2	6.3	9.9	10.5
Parking attempt	5	0.0	0.0	3.1	6.6	7.9
Parking attempt	6	0.0	0.0	1.6	4.5	5.9
Parking attempt	7	0.0	0.0	0.8	3.0	4.4
Parking attempt	8	0.0	0.0	0.4	2.0	3.3
Parking attempt	9	0.0	0.0	0.2	1.3	2.5
Parking attempt	10	0.0	0.0	0.1	0.9	1.9
Total driving distance (m)		521	641	994	1,396	1,606

This manageable additional burden for the telecommunication network is negligible, as a proportional shared use calculation would hardly exist. Further, this infrastructure does not have to be set up specifically for the "Park&Joy" application and is regarded given as well as an end user device (e.g. smartphone, tablet). However, for the development of a multi-criteria and parameterizable method for modelling emission savings the determination of emissions for the vehicles concerned is essential (Table 26.4).

26.3.1 Vehicle Fleet and Its Emissions

In order to be able to calculate possible emission savings, detailed information on the vehicle population, in particular on fuel type, vehicle class and vehicle age for the entire fleet mix in Germany is required. With the help of annual statistics published by the Federal Motor Transport Authority, the following information on registered vehicles could be compiled.

Since the market share of fuel types other than petrol and diesel is less than 2%, these are neglected for the aggregation of all passenger cars registered in Germany. When considering the vehicle age, which is essential for estimating the consumption of the vehicle engine, an average age of 9.4 years was determined (Federal Motor Transport Authority Germany 2018a). Contemplate the average consumption of the vehicle class, the average vehicle age, the share of the vehicle class in the total fleet and the fuel type, an average value of 6.7 l/100 km for petrol passenger cars and 4.4 l/100 km for diesel passenger cars was calculated (Federal Motor Transport Authority Germany 2018b).

For the entire vehicle fleet in Germany, this consumption results in CO2 emissions of 0.169kgCO2/km. However, as these calculations are consumption figures from manufacturers and the scenario calculation only considers parking traffic in cities, these figures have to be supplemented by two additional factors. For the stop-and-go traffic in the city the factor 1.3 is estimated and for the calculation of the real driving emissions (RDE) the factor 1.3 is set as well (Federal Environment Agency Germany 2019). This results in average CO_2 emissions of 0.285 kg CO_2/km.

To calculate the NO_x emissions, an identical approach was applied examining the share of the fuel type and the share of respective pollutant class (Euro 3, 4, 5, and 6) of the entire fleet (Federal Motor Transport Authority Germany 2018c). For diesel vehicles, accurate RDE values are accessible, which were used to preferably ensure a realistic calculation (Federal Environment Agency Germany 2019). Unfortunately, the Federal Environment Agency of Germany does not provide an adequate value adjustment for petrol vehicles. For this reason, the threshold values of the various pollutant classes were used at this point (Federal Environment Agency Germany 2016). Based on this, the calculation of average NO_x emissions for passenger cars in Germany results in 265 mg NO_x/km.

Note, that these emission values of the complete combustion include the whole upstream chain of manufacture and are based on ProBas Database of the Federal Environment Agency (Federal Environment Agency Germany 2015) (Fig. 26.3).

26.3.2 Simplified Life Cycle Assessment of the Sensor

The simplified life cycle orientated environmental assessment, based on the disassembly process and the CT images, is characterized by a detailed material determination. The scope of the study includes the provision of raw materials, the manufacture of components, battery charging and the rollout of sensors. The number of layers of the printed circuit board, the die areas on the printed circuit board, the number and type of active and passive components on the printed circuit board, the materials of the housing and the type and size of the battery are decisive for determining

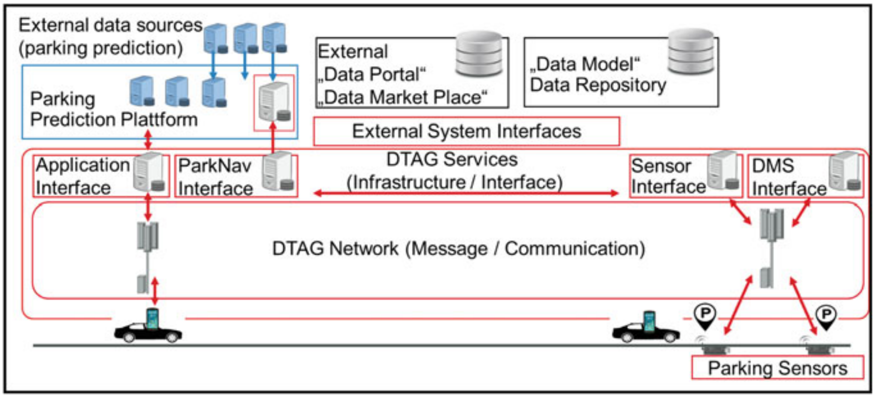

Fig. 26.3 Functional principle of the "Park&Joy" architecture

the emission during the production of the sensor. With the creation of a process-related model of physical components and energy flows in the GaBi LCA software (Thinkstep 2019) the sensor emissions are determined and shown in Fig. 26.4. The lithium thionyl chloride battery (Li–$SOCl_2$) used in the sensor had to be evaluated with a Li–Ion battery data set, as the GaBi database does not prevent a more appropriate data set. Excluded from consideration are reed switch (containing rare earth materials), assembly and transport of the sensor as well as disposal or recycling. An extraction from the street segment after deploying neither for a reuse scenario nor recycling is intended by the operator. Either not possible is the recharging or changing of the battery.

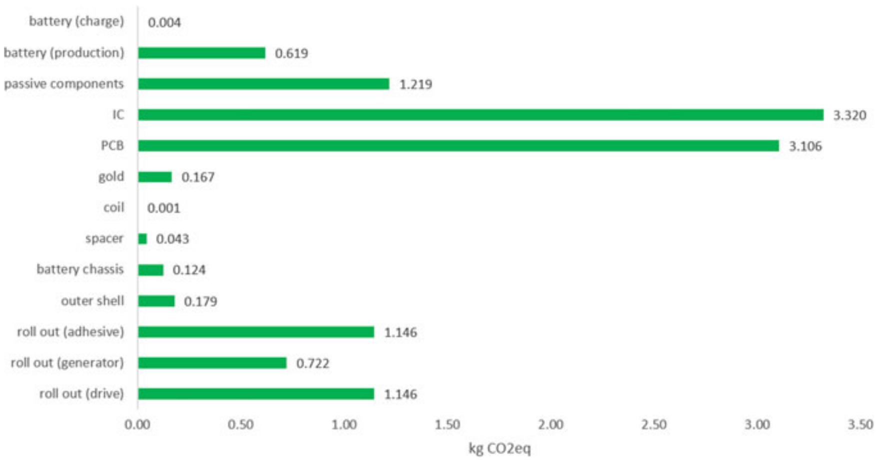

Fig. 26.4 GWP of one sensor

The approach route of the road maintenance department, the used generator for drilling and the polyurethane sealing the drill hole, characterizes the environmental assessment of the whole roll out process. This roll out process is essential to calculate a Global Warming Potential (GWP) for the sensor used within "Park&Joy". In comparison with the materials of one sensor, the roll out is about 34% of the total sensor environmental impact, as seen in Fig. 26.4. Though, the approach route vary from city to city, as different road maintenance departments are in response. The calculated GWP for the driven kilometers for the roll out are orientated towards the conditions of the city of Hamburg.

In summary, one sensor has a GWP of 8.8 kg CO_2eq. Including the roll out the GWP increases to 11.8 kg CO_2eq per sensor. The study shows by far the highest environmental impact for chips (3.3 kg CO_2eq) and printed circuit boards (3.1 kg CO_2eq), followed by passive components (1.2 kg CO_2eq) and polyurethane (1.1 kg CO_2eq), which is used to attach sensors to the asphalt. Since the production of the battery has a much higher global warming potential than the initial charge and the sensor design does not provide for further charging cycles or battery replacement, a functioning power management is both economically and ecologically relevant.

26.3.3 Simplified Life Cycle Assessment of the Server

The server infrastructure, as described in Sect. 2.2, is static and does not scale with increasing number of sensors. Hence, the preparatory study for implementing measures of the Ecodesign Directive (Berwald et al. 2015) in combination with the evaluated server infrastructure allows to calculate a GWP for server use per year of 12,268.17 kg CO_2eq.

However, the influence of a possible increasing environmental burden through growing or multiplying compute centers for the "Park&Joy" application is investigated in Sect. 5.3.

26.4 Cost-Benefit Model

The cost-benefit model bases on the methodical approach of the hardware's simplified life cycle assessment in combination with a probability model of a parking attempt and some assumptions for reference scenario. The reason to use this approach is to provide a detailed comparison of cost from manufacture and operation of "Park&Joy" (CO_2 emission of sensor and server systems) and benefit from the saved driving kilometers (CO_2 and NO_x emission).

26.4.1 Methodology for the Hamburg Scenario

In order to calculate possible emission savings creating a reference scenario is crucial. The server systems for the “Park&Joy” application are completely set up and in operation. However, the sensors are not yet fully installed in any major German city for comprehensive use. And it is important that these sensors are currently intended to cover street parking lots exclusively without considering car parks or private parking areas.

To scale the required number of sensors, planning values from Deutsche Telekom need to be used. Only for the city of Hamburg these values are fully available. A total of approx. 1300 sensors, covering approx. 11,000 parking lots, are intended to be used here. This information in combination with the number of inhabitants enables not only the calculation that each sensor covers 8.46 parking lots, but also that 0.0061 parking lots per inhabitant are available in Hamburg. The number of daily parking operations per parking lot is assumed to be 6 as an average annual mean value for a simplified calculation. This is an estimated value, as daily and seasonal differences in parking behavior as well as parking time restrictions vary greatly in some cases (Rikus et al. 2015). The server lifetime in the Hamburg scenario is set to 4 years (Berwald et al. 2015). Depending on the application (active and sleep time) and quality of the local mobile telecom network, the sensor lifetime for “Park&Joy” is projected 4 years as well.

With these values from the Hamburg planning scenario, fast projections can also be carried out for other cities in Germany. Of course, these projections have to be considered differentiated, since the number of parking lots covered by a sensor depends very much on the geographical environment and the condition of the corresponding street segment. Also, the scaling of the number of parking lots on the basis of the number of inhabitants permits only rough calculation. When the rollout took place in Hamburg and other cities and first real data are available, these assumptions can be adjusted accordingly and the model can be refined.

A major challenge in modelling is the definition or mapping of the parking process. In particular, the time at which a search process starts and the average speed driven during the search for a parking lot are difficult to determine. Major disparities of cities for example in commuter traffic or the road network have an influence on the parking situation and the variance of parking search times (Cookson and Pishue 2017). For this reason, an easily modifiable probability model is used at this point until a well-founded real data basis is available to specify the model properly.

According to its own information, Deutsche Telekom’s predication server for the “Park&Joy” application provides a probability of success for finding a parking lot of 96% in connection with the sensor data and 78% with exclusive use of the traffic data without additional sensor support. With the conceding of a driving distance of 500 m per parking attempt, these probabilities of success can be used to determine a total distance for a parking process.

The two most important values taken from Table 26.4 are 521 m for a parking attempt with “Park&Joy” and 1,396 m for a conventional parking attempt without any guidance. This principle approaches that low probability of finding a parking space leads to a covered longer distance and therefore, more emissions are emitted. In the city of Hamburg, the average yearly search time for parking lots is 52 h per driver (Cookson and Pishue 2017). Hence, assuming an average speed of approx. 30 km/h, the daily search attempt is around 1,200 m within an 8.5-minute-long drive. This nearly fits the probability model value of 33% probability of success without "Park&Joy" application and is considered as a confirmation for the model. However, the total driving distance is a rough assumption contributing a rapid model creation with the opportunity of improvement in the data base after additional information from the "Park&Joy" system is available.

26.4.2 Emission Saving Calculation

With the GWP of the server infrastructure, the sensors and the probability model of parking attempts, it is possible to calculate cost, benefit, amortization and the emission balance. For the city of Hamburg, the whole infrastructure for "Park&Joy" costs around 17t CO_2eq per year. This result includes the manufacturing of all necessary server proportionate per year, the usage of all server per year and the manufacturing, rollout and usage of all sensors proportionate per year in depending overall hardware lifetime. If every parking process in the city is performed with "Park&Joy" guidance 21 million driving km can be saved. This saving equals about 6,000t CO_2eq and 5,6t NO_x per year. In Fig. 26.5 the different savings depending on market share are shown in a period under consideration of one year.

The probability that all parking processes will be performed with "Park&Joy" is conceded low. Therefore, no absolute emission savings can be determined. It is a differentiation of saving potentials depending on several influencing factors. Analog to Fig. 26.5 the NO_x emission savings are shown in Fig. 26.6. Note, that

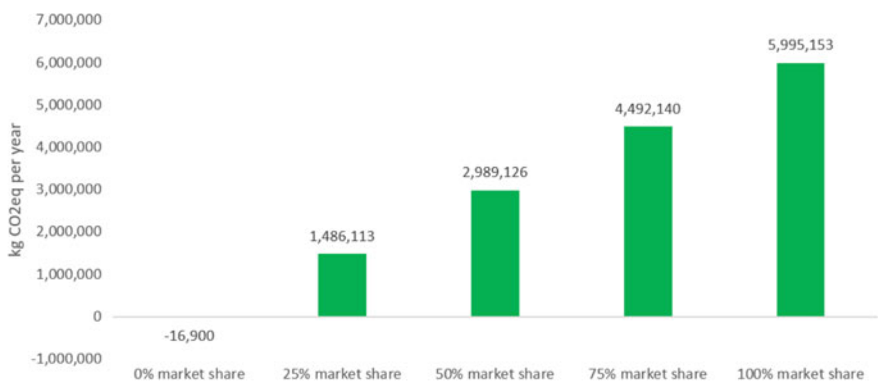

Fig. 26.5 CO_2 emission savings of "Park&Joy" per year

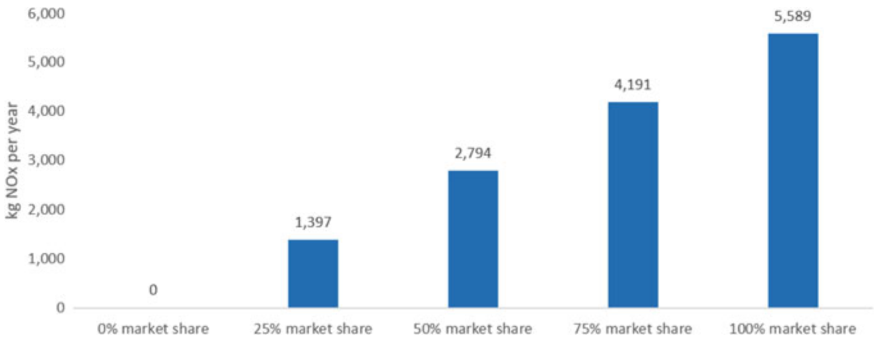

Fig. 26.6 NO_x emission savings of "Park&Joy" per year

no calculation was carried out to figure out NO_x emissions for manufacturing and operating of servers and sensors. Hence, the NO_x emission saving can never reach a value lower than zero.

A point of amortization, defined as the minimum necessary usage of "Park&Joy" to compensate the CO_2 emissions emitted, can indicate the meaningfulness of an implementation. In Hamburg approx. 60,000 km or 115,000 parking operations are necessary to achieve this point. These values correspond to a market share of 0.28%, at which the amortization point is reached. This methodology allows rough but quick calculations for any other city in Germany by applying population information for the amount of parking lots.

In Tables 26.5 and 26.6 the emission saving potential of "Park&Joy" for Berlin and Munich are figured as projections of the Hamburg scenario.

The geographical conditions in different cities lead to a different number of covered parking lots per sensor, which is an influent value on the overall calculation. Also, using an extrapolation for the number of parking lots is indicative as the realization of "Park&Joy" in different cities will be defined by piecewise implementation for firmly defined parking areas.

These projections show that with increasing traffic volume the potential emission savings increase too and lead to a lower point of amortization. For the 80 biggest cities in Germany the amortization rate never exceeds 5%.

Table 26.5 "Park&Joy" emission saving potential Berlin

	Value	Unit
Number of sensors	2,568	pcs
Parking lots	21,721	pcs
Max. CO_2 emission savings (100% market share)	11,850,981	$kgCO_2eq/a$
Max. NO_x emission savings (100% market share)	11,035	$kgNO_x/a$
Emission costs	20,636	$kgCO_2eq/a$
Amortization	0.17	%

Table 26.6 "Park&Joy" emission saving potential Munich

	Value	Unit
Number of sensors	1,052	pcs
Parking lots	8,897	pcs
Max. CO_2 emission savings (100% market share)	4,846,492	$kgCO_2eq/a$
Max. NO_x emission savings (100% market share)	4,520	$kgNO_x/a$
Emission costs	16,165	$kgCO_2eq/a$
Amortization	0.33	%

26.4.3 Influencing Factors

By evaluating the emission saving results, the identification of major influencing factors is necessary to provide a sensitivity analysis of the cost-benefit model. Based on the Hamburg scenario, with 11,000 parking lots and a four-year lifetime span of servers and sensors, four of the following factors show the different influence on the emission savings of "Park&Joy".

Of course, the most important value is the market share, as it defines the ratio between parking operations performed with and without "Park&Joy". However, this value has a high uncertainty, as the rollout of "Park&Joy" is not yet completed and there is no data available on the intensity of use.

With an increasing number of parking operations performed with "Park&Joy" (higher market share), the emission savings also increase, as more than 800 m of driving distance per parking operation can be saved. In Fig. 26.7 it is clearly recognizable, that CO_2 emission savings are already achieved with a low market share.

If an increased traffic volume and thus more frequented parking lots are assumed, the emission savings will also increase. Figure 26.8 show the high influence of the parking attempts per day on the emission saving results. Unfortunately, this factor has the highest uncertainty in the calculation.

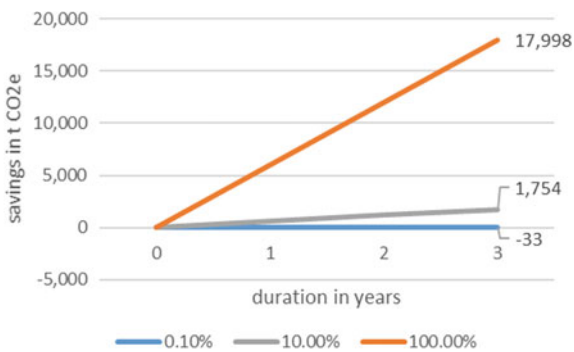

Fig. 26.7 Sensitivity analysis—market share

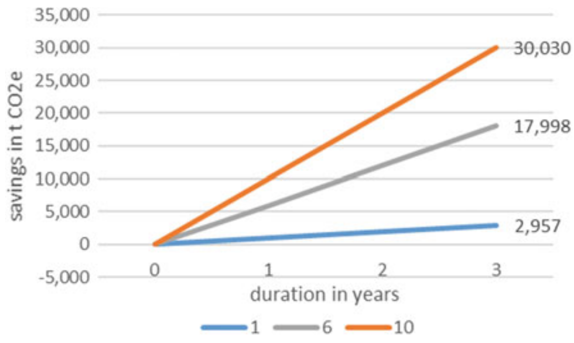

Fig. 26.8 Sensitivity analysis—parking attempts per day

Figure 26.9 examine the covering rate of parking lots per sensor. If a city or street segment does not allow a sensor to cover 8 or more parking lots, its density in the asphalt needs to be increased. Due to the relatively low CO_2 emissions during sensor production, the installation of a higher number of sensors has hardly any noticeable effect on the savings potential of the emissions. Note, a possibly scaled success probability by an increased sensor number is not considered in this calculation (Fig. 26.10).

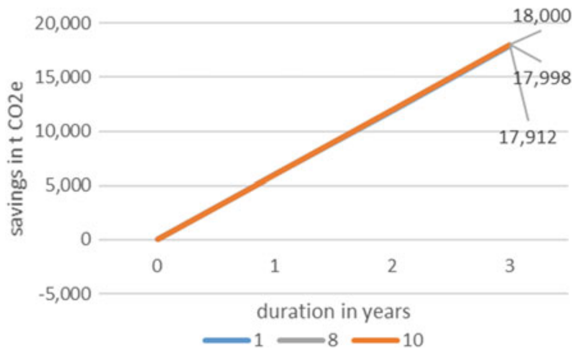

Fig. 26.9 Sensitivity analysis—parking lots per sensor

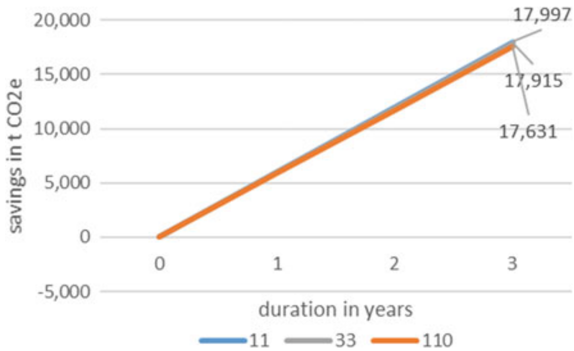

Fig. 26.10 Sensitivity analysis—number of servers

The last major factor to examine is the assumption of a massive rising number of servers. Even assuming a tenfold increase in the number of necessary server systems, no significant influences on emissions are discernible. This observation is attributed by the proportionally low emissions of the servers compare to emissions of vehicles, analogously shown with the behavior for the parking lots per sensor.

In summary, potential CO_2 savings scale with the market share of the "Park&Joy" Application and the probability of parking lot forecasts. The change of real vehicle emissions through increasing numbers of electric vehicles or stricter limits for inner cities and the average number of parking searches per day are scaling factors as well. The emission savings also scale with the actual parking search time and the speed-dependent distance travelled. A slightly influence consists in the number of parking lots covered by a sensor, as the environmental impact of the sensors is comparatively small. And as a minor influence factor the lifetime of sensor and server infrastructure was detected, which are calculated proportionately in the total balance.

26.5 Summary

The initial idea of the sensor as the central element of the cost-benefit analysis leads to an examination in great detail. It turned out that spending less effort on the sensor investigation would be appropriate, since the ratio of emissions compare to traffic is rather low.

The complete calculation is implemented in software. In the developed tool, the greatest uncertainties can be adjusted and the main influencing factors of the emission saving can be varied to describe exactly the target scenario (e.g. certain geographical area). In combination with a future data collection to determine real driving emissions with permission of the customers, as well as the statistically record start and end of app usage to determine real parking search distances, the tool can achieve even higher accuracy. In addition, a yearly update of vehicle fleet composition of Germany leads to a more precise calculation of saving potentials. While disassembling the sensor some potential hardware improvement has been identified. The plastic welding of the current design obstructs the recycling and maintenance of possible defective components. As the battery and the primary board are located right next to each other (Fig. 26.1) along the welding edge, a non-destructive opening is not possible. Currently, all sensors remain in the asphalt after end of life. Hence, the most important issue is the complete loss of valuable materials, as neither the manufacturer nor operator provide any reuse, renew or recycle option for the sensors. However, the study shows the emission saving potential in Germany's inner cities by using "Park&Joy" is rather high and reasonable.

In summary, a multi-criterion and parameterizable method for modelling the emission savings was developed and implemented in software. The environmental assessment lacks a proportional consideration of the resource consumption, since a direct comparison with the vehicle emissions is not possible. It should be borne in mind that resource consumption is always a factor that cannot be offset by the number of kilometers travelled. The data basis is considered to be robust, but due to data gaps well-founded assumptions had to be made. The greatest uncertainty exists with regard to real driving emissions. It is now possible to use real measurement data from the pilot project to verify the scenarios and adjust them if necessary.

"Park&Joy" is a very good example of "Green through IT", with high environmental benefit through a smart city application. But the study also shows that environmental benefit and effort need to be determined and quantified precisely. The presented methodology will be used to evaluate further smart city applications and hence extended and refined continuously.

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Chapter 27
Scenario Analysis of Environmental Impact of Paddy Rice Farming Systems Utilizing Different Fertilizer Materials

Tatsuo Hishinuma, Saaya Ono, and Atsuo Ikeguchi

Abstract Assessment of the environmental impact of applying materials to the paddy rice farming system is crucial to the promotion of low inputs of chemical fertilizers and crop protection chemicals, and encouraging the application of composted livestock manure. In this study, we assessed greenhouse gas emissions, total nitrogen and total phosphorus losses from soil, and acidification gas emissions from paddy rice farming systems using different inputs, employing scenario analysis and life-cycle assessment strategies. Scenario analysis of farms in Shiga prefecture indicated a lower environmental impact from paddy rice farming systems using organic fertilizer compared with conventional systems. On the other hand, the environmental impact from the paddy rice farming systems in Tochigi prefecture using composted manure was greater than that from systems applying chemical fertilizers.

Keywords Paddy rice production · LCA · GHG emission · Eutrophication · Scenario analysis

27.1 Introduction

Rice paddies are one of the major causes of environmental impact, contributing to global warming and water body eutrophication caused by excessive inputs of nitrogen and phosphorus. Methane emission, which has a very large global warming impact, was estimated to be 13.9 Mt-CO_2e (representing 9% of total agricultural GHG emissions) from rice paddies, and CH_4 emissions have increased in Japan, compared with those at benchmark year (12.7 Mt-CO_2e, 1990) (Greenhouse Gas Inventory Office of Japan 2018). The loss of nutrients from fertilizer applied to rice paddies increases the total nitrogen (T-N) and total phosphorus (T-P) in water bodies through leaching and runoff. Recently, paddy rice farming systems that reduce artificial inputs (chemical fertilizers and crop protection chemicals) by applying organic fertilizers and composted livestock manure have been developed as an example of environmentally

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protective conservation-type agriculture. The quantity of artificial fertilizers and crop protection chemicals applied to agricultural fields in these systems were 91 kg N/ha and 56 kg/ha, respectively, reductions of 60–70% from the amount of these inputs used in 1992 (Ministry of Agriculture Forestry and Fisheries 2018).

On the other hand, applying organic fertilizers or composted livestock manure to agricultural fields could lead to excess levels of nutrients in the soil, because the use of low-nutrient compost requires the application of much larger volumes, compared with the high-nutrient artificial fertilizers (Mishima and Kimura 2004). In addition, the input of organic fertilizer to rice paddies, instead of artificial fertilizers, increases methane emissions (Masuda and Tomioka 2013). Furthermore, the environmental impact associated with the agricultural system should take into account not only direct emissions from agriculture, such as greenhouse gas and acidification gas emissions, and nitrogen and phosphorus leaching from the soil, but also indirect emissions, such as from the manufacture of such inputs.

The life-cycle assessment (LCA) technique is a useful measure to reveal the environmental impact of component elements of agricultural production systems. Because the production of artificial fertilizers and crop protection chemicals consumes large amounts of fossil fuel, low-input agriculture can be effective at mitigating eutrophication and reducing global warming potential, such as with conservation paddy rice farming systems (Kurosawa et al. 2007).

In this current study, we evaluated the environmental impact of paddy rice farming systems, comparing conservation-type systems applying organic fertilizers or composted animal manure relative to the use of artificial inputs in a conventional system, using scenario analysis with process-based LCA.

27.2 Materials and Methods

27.2.1 Framework of Evaluation

In this study, LCA and farmgate balances (FGB) approaches were used to quantify the environmental impacts from different paddy rice farming systems, in terms of gas emissions and the potential of T-N and T-P leaching into water bodies (Fig. 27.1). The process model of the paddy rice farming system was set as the same, to compare the environmental impacts between the environmental conservation-type system and the conventional type system with respect to the differences in inputs, ignoring the differences in working processes and machinery usage. The collected data and amounts of inputs and rice yield from each scenario were applied to the process model and were assessed in terms of environmental impacts, using LCA and FGB. The LCA technique is a method by which environmental aspects and the potential impacts of a production system (considered as a process chain) can be analyzed throughout a product's life-cycle (ISO 2006). In this study, environmental impacts from the different rice paddy farming systems were compared by scenario analysis using the LCA method,

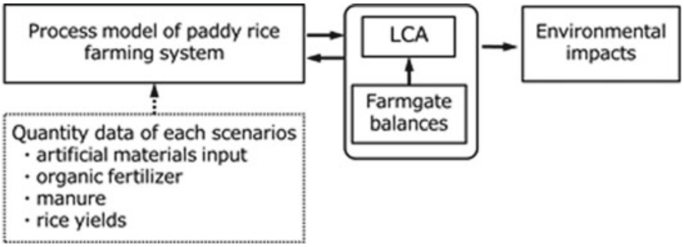

Fig. 27.1 Framework of evaluation

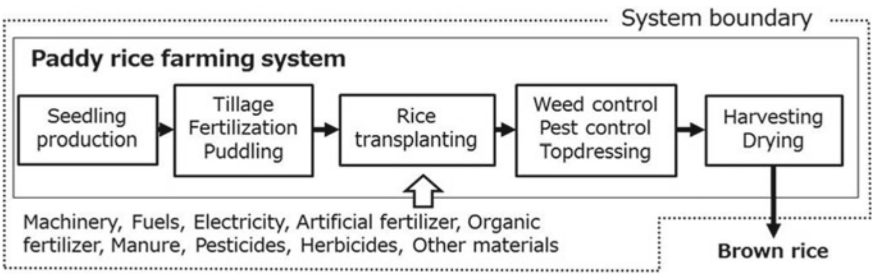

Fig. 27.2 Process model and system boundary of paddy rice farming system

enabling quantitative description of the environmental impacts of resource materials, fertilizer materials, and agrochemicals in terms of production and consumption. The FGB technique is a method to calculate N and P surplus across fields within a farm by calculating the difference between nutrient input and output (Van Beek et al. 2003). In particular, the FGB method has been used to estimate the amounts of nitrogen and phosphorus lost from rice paddies, which are difficult to determine because they are influenced by agricultural management.

We assessed GHG emissions, the potential of T-N and T-P losses for causing eutrophication (EP), and acidification gas (AG) emissions. The GHG emissions were evaluated using global warming potential values, GWP_{100} (CO_2: 1, CH_4: 34, N_2O: 298) (IPCC 2013). The environmental impact characterization factors for EP (T-N: 0.26, T-P: 3.06), and AG (nitrogen oxides (NO_x): 0.72, sulfur oxides (SO_x): 1) were based on LIME2 (Itsubo and Inaba 2010). The functional unit for evaluation of environmental impacts from the paddy rice farming system was defined as 1 ha of rice paddy and 1 kg of harvested brown rice, for assessing impacts from input materials and yields, respectively.

27.2.2 Process Model of Paddy Rice Farming System

The process model and system boundary analyzed in this study are shown in Fig. 27.2. The process model assumes a system of family farming, operated around 20 ha of rice paddies including contract paddy farming, using medium-type-operation machinery, a 60 PS tractor, a six-row rice transplanting machine and a four-row combine harvester. In Japan, the expansion of rice paddy production scale by local core farmers used rice paddies from small-scale farmers or retired farmers to achieve the effective operation size for rice paddy production. The process model reflects the case of the local core farmer contracting paddy rice farmland from neighboring small-scale farmers.

27.2.3 Estimation of Potential Nitrogen and Phosphorus Loss, Using FGB

The sources of nitrogen input to rice paddies are fertilizer, straw, irrigation water, and rainwater. The nitrogen output from the rice paddy is in the forms of rice, hulls, straw, N_2O emission, N_2 and NH_3 emission, and T-N loss with leaching into surface and groundwater. Furthermore, some nitrogen remains in the soil as residues (Fig. 27.3).

In this study, because of the objectives to evaluate the environmental impacts of the differences in quality and quantity of the input material, nitrogen from the natural nitrogen sources (irrigation water and rainwater) were not considered. In addition, the nitrogen flows of the rice straw were assumed to be balanced in the rice paddies, because the harvested straw is incorporated into the soil by the plowing practices of the tillage process in most of the paddy rice farming systems in Japan.

Therefore, the T-N loss from rice paddies was calculated as the N loss potential which was the nitrogen remaining after deduction of nitrogen from the protein content of rice and the N_2O emission from the rice paddies from the nitrogen input in the

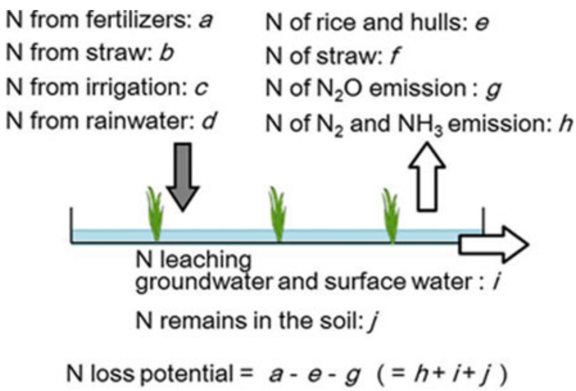

Fig. 27.3 Estimation of N loss potential by farm gate balance (FGB) method

form of fertilizers (Fig. 27.3). The P loss potential in rice paddies was estimated similarly to N loss estimation, with the nitrogen and phosphorus contents of rice grain and hulls being determined from the ingredient database of biomass (National Research Institute of Agricultural Engineering 2006).

27.2.4 Data Source and Scenario of Paddy Rice Farming Systems

The amount of the agricultural material consumption data of the process model for the paddy rice farming system by life-cycle inventory analysis was collected from statistically based data (AFFTIS 1997). The environmental conservation practices evaluated in paddy rice farming were of two types: (1) using organic fertilizer and reduced crop protection chemicals (practices at Shiga prefecture), and (2) using composted farmyard manure instead of artificial fertilizers (practices at Tochigi prefecture).

(1) *Scenario analysis of organic fertilizer application in the paddy rice farming system*

In Shiga prefecture, environmentally friendly conservation-type practices are applied to the paddy rice farming system. The organic fertilizer is made from organic residuals, such as feather meal and rapeseed oil cake, that has a nutrient composition similar to that of artificial fertilizers, and that is markedly higher than that from composted animal manure.

In the analysis of the organic fertilizer application scenario, we evaluated the environmental impacts of these conservation practices, that reduced the amount of artificial fertilizers and crop protection chemicals applied to less than 50% of the rate used in the conventional paddy rice farming system. The data used in the process model for comparing environmental impacts between the organic fertilizer use scenario and the conventional scenario were collected from the research report of field experiments in Shiga (Table 27.1) (Hasukawa et al. 2009).

The conventional scenario utilized 450 kg/ha of artificial fertilizers, with the amount of nitrogen applied being 76 kg/ha, whereas the total amount of crop protection chemicals used was 38.9 kg/ha, consisting of 14 different components. The yield of brown rice was 5670 kg/ha from the conventional scenario. The organic fertilizer application scenario used 800 kg/ha of organic fertilizer, representing 70 kg/ha nitrogen being applied. The crop protection chemicals were applied to the organic fertilizer scenario at a total of 16.6 kg/ha for six components. The difference in the brown rice yield from the two scenarios was minimal. The yield of brown rice was 5460 kg/ha at the organic fertilizer application scenario. The target yield from environmental conservation-type paddy rice farming system was 7400 kg/ha under the guidelines for rice production in Shiga. Hence, both scenarios were acceptable for analysis in this study, from the quantitative point of input materials and production yield.

Table 27.1 Amount of input materials in the paddy rice farming scenario at Shiga prefecture

Scenario		Conventional		Organic fertilizer	
Base fertilization		Artificial fertilizer	P fertilizer	Organic fertilizer	P fertilizer
	Application rate [kg/ha]	250	800	500	493
	(N–P–K)	(40–13–25)	(0–21–0)	(40–11–21)	(0–13–0)
Additional fertilization		Artificial fertilizer		Organic fertilizer	
	Application rate (kg/ha)	200		300	
	(N–P–K)	(36–3–17)		(30–8–25)	
Seed sterilization	Number of components	3		–	
	Application rate (kg/ha)	2.3			
Herbicides	Number of components	7		3	
	Application rate (kg/ha)	15.2		5.2	
Pesticides	Number of components	4		3	
	Application rate (kg/ha)	21.4		11.4	
Brown rice yield (kg/ha)		5670		5460	

(2) *Scenario analysis of manure application to the paddy rice farming system*

Composted animal manure is widely applied to agricultural fields to achieve increased soil nutrient content and is promoted by laws and ordinance as the practice for environmental conservation-type agriculture.

Using scenario analysis, we compared the environmental impact of the paddy rice farming system when applying composted livestock manure instead of artificial fertilizers with a conventional system using artificial fertilizers. The analysis compared environmental impacts through three fertilizer scenarios: artificial fertilizer, manure and artificial fertilizer, and manure. The amounts of input materials and rice yield for each scenario for analysis were collected from the experimental report of paddy rice yields under continuous manure application on full-scale fields in Tochigi (Table 27.2) (Maeda 2001).

The artificial fertilizer scenario utilized 1117 kg/ha of artificial fertilizers, with the amount of nitrogen applied being 98 kg/ha. The manure scenario used 32,000 kg of manure, of which the nitrogen input was 694 kg/ha. At the manure and artificial fertilizer scenario, artificial fertilizers were inputted at 518 kg/ha, and manure at 32,000 kg/ha, with the total nitrogen input being calculated at 741 kg/ha. The input

Table 27.2 Amount of input materials at the paddy rice farming scenario at Tochigi prefecture

Scenarios		Artificial fertilizer	Manure and Artificial fertilizer		Manure
Base fertilization		Artificial fertilizer	Manure	Artificial fertilizer	Manure
	Application rate (kg/ha)	998	32,000	459	32,000
	(N–P–K)	(76–87 – 182)	(694 – 306–749)	(36–86–83)	(694 – 306–749)
Additional fertilization		Artificial fertilizer	Artificial fertilizer		–
	Application rate [kg/ha]	119	59		
	(N–P–K)	(22–0–16)	(11–0–8)		
Herbicides	Number of components	3	3		3
	Application rate (kg/ha)	10	10		10
Pesticides	Number of components	1	1		1
	Application rate (kg/ha)	30	30		30
Brown rice yield (kg/ha)		4910	5220		3830

of crop protection products and the number of components were the same for the three scenarios.

The quantity of manure applied (32,000 kg/ha) in the compost and artificial fertilize scenario and in the compost scenario was more than three times the baseline application level of fertilizer materials (10,000 kg/ha) in Tochigi. Furthermore, the brown rice yield in the manure scenario was low (Table 27.2). Whereas the data collected were characteristic from the point of manure quantity applied in the paddy rice farming system, the data were available to use the analysis to clarify the environmental impacts from the different scenarios of fertilizer material utilization.

27.2.5 Data Source of Background Data

Most of the background data for inventory analysis were from the database of the IDEA ver. 2.2 (AIST and JEMAI 2018), which mostly represents Japanese production. The emission factors of CH_4 or N_2O associated with agricultural practices at rice paddies, such as plowing, and fertilizer application, came from the National Greenhouse Gas Inventory Report in Japan (Greenhouse Gas Inventory Office of

Japan 2018). The GHG emissions associated with the use of agricultural machinery, the indirect emissions, were calculated based on the operating hours and economic life of machinery.

27.3 Results and Discussion

The range of GHG emissions from the results of LCA of the entire scenarios were 3283–5343 kg-CO_2e/ha. These values were similar to the reported GHG emissions, namely 2270 kg-CO_2e/ha (Hokazono et al. 2012) and 5870 kg-CO_2e/ha (Kurosawa et al. 2007) estimated using the LCA method. Basically, the values from the LCA reflected emissions from consumed materials, hence the similarity between our results and the reported values are considered to support the discussions based on the outputs from our scenario analysis.

27.3.1 Comparing the Environmental Impacts Between Organic Fertilizer and Conventional Scenarios

The GHG emissions from the conventional scenario were 5343 kg-CO_2e/ha, of which 59.7% was caused by indirect emission during artificial fertilizer production. The GHG emissions from the organic fertilizer scenario were 3735 kg-CO_2e/ha, 33% less than that from the conventional scenario (Fig. 27.4). The GHG emissions associated

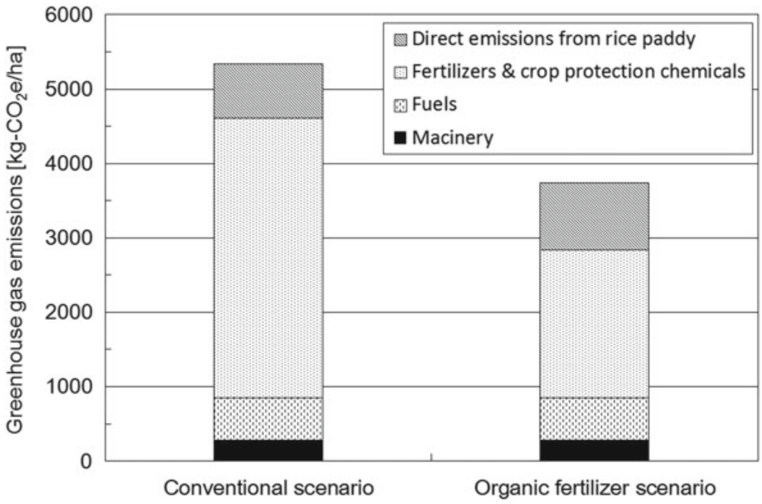

Fig. 27.4 Comparison of greenhouse gas (GHG) emissions between the organic fertilizer scenario and the conventional scenario

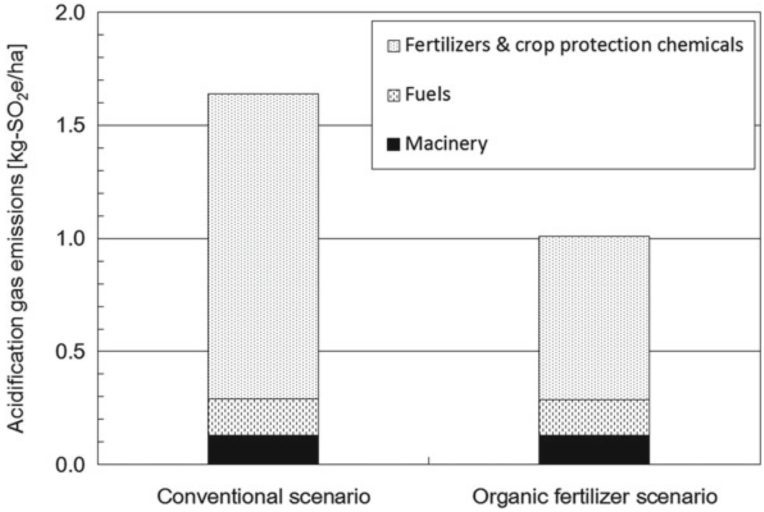

Fig. 27.5 Comparison of acidification gas (AG) emissions between the organic fertilizer scenario and the conventional scenario

with brown rice production from the conventional and the organic fertilizer scenarios were 0.94 and 0.65 kg-CO_2e/kg rice, respectively.

The AG emissions from the conventional scenario were 1.64 kg-SO_2e/ha, of which 82.3% was caused by indirect emission during artificial fertilizer production. The AG emissions from the organic fertilizer scenario were 1.01 kg-SO_2e/ha, 38% less than that from the conventional scenario (Fig. 27.5). The AG emissions associated with brown rice production from the conventional and organic fertilizer scenarios were 0.29×10^{-3} and 0.19×10^{-3} kg-SO_2e/kg rice, respectively.

The eutrophication impacts were 64.5 kg-$PO_4{}^{3-}$e/ha in the conventional scenario, and 50.1 kg-$PO_4{}^{3-}$e/ha in the organic fertilizer scenario (Fig. 27.6). The N loss potential was calculated to be 10.5 kg-N/ha in the conventional scenario and 6.9 kg-N/ha in the organic fertilizer scenario. The dominant sources of eutrophication impact were T-N and T-P loss from fertilizer materials applied to rice paddies.

The rice yields were maintained regardless of the reduced artificial fertilizer input at an organic fertilizer scenario. The environmental impact from an organic fertilizer production system was lower than that from an artificial fertilizer production system, indicating that the environmental impact of fertilizer application was mitigated in the organic fertilizer scenario in general. Replacing artificial fertilizers with organic fertilizers was effective in reducing environmental impact.

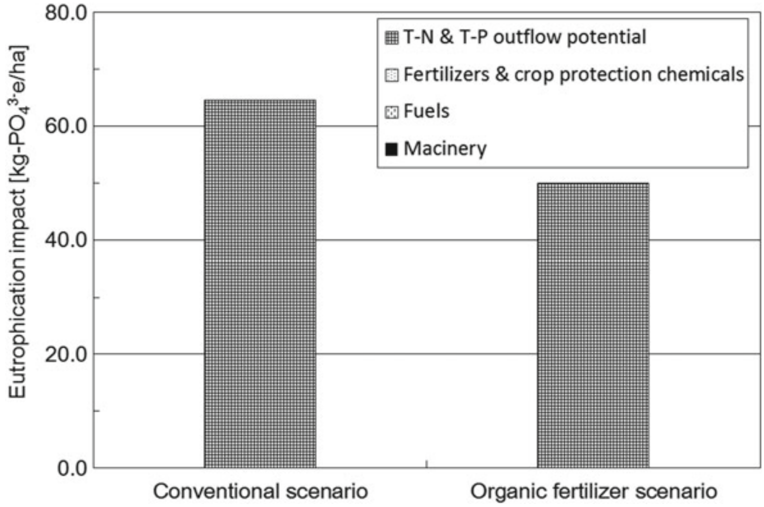

Fig. 27.6 Comparing eutrophication impact from the organic fertlizer scénario to conventional scenario

27.3.2 Comparing Environmental Impacts of the Manure Scenario and Artificial Fertilizer Scenario

The GHG emissions from the manure and artificial fertilizer scenario and the manure scenario were 6189 kg-CO_2e/ha and 5462 kg-CO_2e/ha, respectively, increasing by 1.9 and 1.7 times, respectively, compared with the emissions from the artificial fertilizer scenario (Fig. 27.7). In particular, direct N_2O emissions from the manure scenario were 2 to 2.5 times higher than those from the artificial fertilizer scenario, whereas the CH_4 emissions from the rice paddies were 31 times higher in the manure scenarios than in the artificial fertilizer scenario. The GHG emissions associated with brown rice production were 0.67 kg-CO_2e/kg rice from the artificial fertilizer scenario, 1.19 kg-CO_2e/kg from the manure and artificial fertilizer scenario and 1.43 kg-CO_2e/kg from the manure scenario.

The AG emissions from the artificial fertilizer scenario were 0.91 kg-SO_2e/ha, compared with the scenarios involving application of manure (1.3 kg-SO_2e/ha) and manure plus artificial fertilizer (1.6 kg-SO_2e/ha) (Fig. 27.8), with the corresponding AG emissions on a rice yield basis being 0.16×10^{-3} kg-SO_2e/kg, 0.30×10^{-3} kg-SO_2e/kg and 0.33×10^{-3} kg-SO_2e/kg, respectively.

The eutrophication impacts were 539.4 kg-PO_4^{3-}e/ha in the artificial fertilizer scenario, 1328.5 kg-PO_4^{3-}e/ha in the manure and artificial fertilizer scenario, and 1070.9 kg-PO_4^{3-}e/ha in the manure scenario (Fig. 27.9). The N loss potential was calculated to be 40.4 kg-N/ha in the artificial fertilizer scenario, 678.1 kg-N/ha in the manure and artificial fertilizer scenario and 647.5 kg-N/ha in the manure scenario,

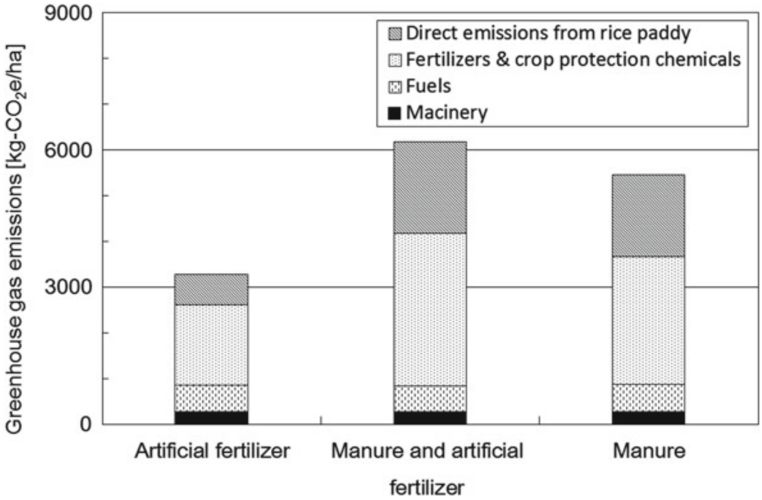

Fig. 27.7 Comparing greenhouse gases (GHG) emissions from three scenarios

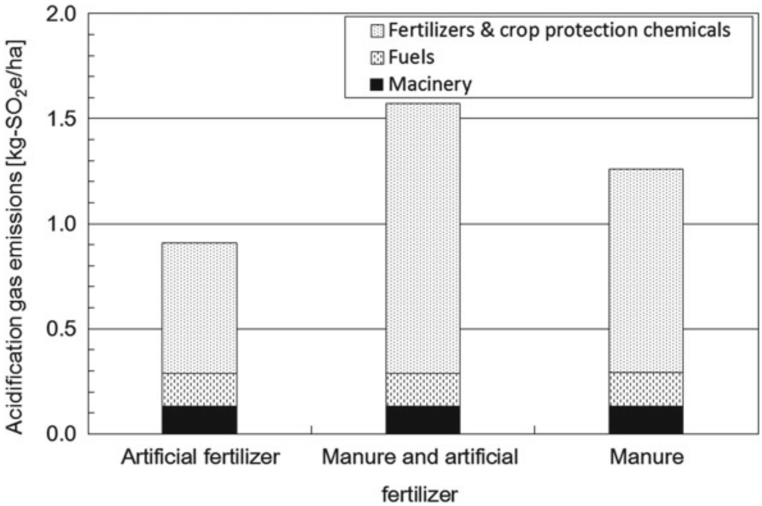

Fig. 27.8 Comparing acidification gas (AG) emissions from three scenarios

with the T-N and T-P loss potentials being considerably higher in both scenarios involving manure.

The results show that the environmental impacts were particularly high in the scenarios in which manure was added. In particular, manure application to the paddy rice farming system led to greatly increased emissions of N_2O and CH_4, two gases which play major roles in climate change because of their high global warming potentials. Because the proportion of nutrients is lower in manure compared with

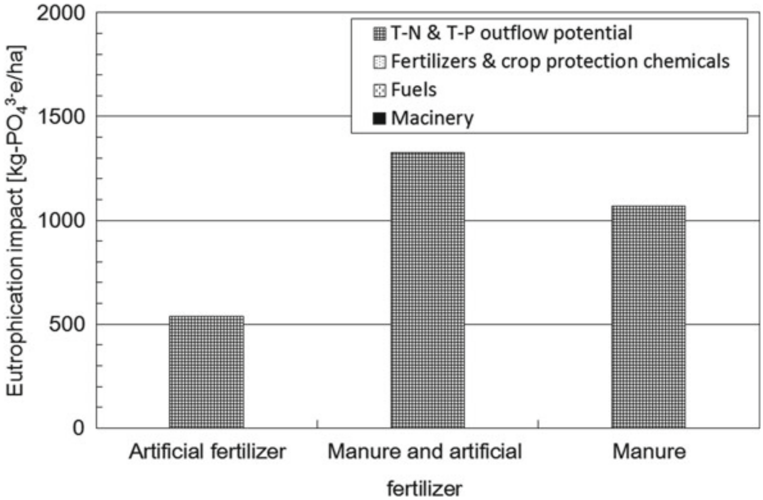

Fig. 27.9 Comparing the eutrophication impact of the organic fertilizer scenario with that of the conventional scenario

artificial fertilizers, a much larger volume of manure needs to be applied to input the same quantities of nutrients compared with what would be needed in the form of artificial fertilizers. Furthermore, the nutrient-use efficiency of the manure is lower than for the artificial fertilizers, resulting in high T-N and T-P loss potentials in the former, which, in turn, lead to higher eutrophication impacts, when applying manure than would be the case when using artificial fertilizers.

27.4 Summary

In this study, to evaluate the environmental impact of GHG emissions and eutrophication caused by nutrient loss from the soil from the environmental conservation-type paddy rice farming system, relative to the conventional system, the framework of analysis was established using the LCA and FGB methods, through scenario analysis.

The results showed that using organic fertilizers instead of artificial fertilizers has potential for reducing the environmental impacts of paddy rice production. On the other hand, the use of composted animal manure resulted in greater GHG emissions and eutrophication due to greater T-N and T-P losses from the rice paddies than occurred with the conventional rice paddy farming systems using artificial fertilizers.

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Chapter 28
Techno-Economic Assessment on Waste from Palm Oil Mill to Electricity in Malaysia

Hashizume Michino and Tokimatsu Koji

Abstract In the production process of palm oil, three types of biomass; Empty Fruit Bunch (EFB), Kernel Shell (KS) and Mesocarp Fiber (MF) are produced as wastes. In real society, many palm oil mills utilize only MF as fuel for internal electricity generation and other biomass are just disposed. We focus on these three kinds of biomass and conduct an economic assessment on utilizing all combined cases of the three biomass not only for internal use of generated electricity but also for selling local area via the grid. We evaluate seven cases; namely, case 1 (utilizing all biomass), case 2 (EFB and MF), case 3 (EFB and KS), case 4 (MF and KS), case 5 (only EFB), case 6 (only MF, generally used currently), case 7 (only KS). Unutilized biomass is assumed transferred to a nearest palm oil mill in simplicity. We estimated costs consisted from direct construction of generating electricity from biomass, operating, maintenance and transportation for the unutilized biomass. We calculated sales for generated electricity by assuming market price and feed-in tariff (FIT). In addition to the power sales, ash from the boiler is also assumed to be sellable as a fertilizer from expecting market price and active ingredient contents in the ash. Following results are clarified; (1) the transportation cost shared largest among all the cases (2) power is the largest among the three sales components (3) the case 1 utilizing all the biomass wastes shows generally largest profit while the case 6 commonly used recently indicates least among the cases.

Keywords Palm oil biomass · Waste to energy · Economic assessment

28.1 Introduction

In south east Asia, their economics are rapidly developing now. Along these rapid economic development, energy demands are also rapidly increasing. However, there

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is no clear way to generate energy for catching these changes of demands up. On the other hand, these economic development are only happened in the city areas. For example, the difference of mean monthly gross household income between city area and rural area is getting bigger in Malaysia. Increased amount of the difference between 2002 and 2012 was 739 MYR, the one in city areas was 43% bigger than the one in rural areas (Chamhuri et al. 2016).

For these two issues in south east, a rapid increase of energy demands and the difference between city area and rural area, biomass energy can be one of solutions since it contributes energy shift as a renewable and sustainable energy. Moreover, there is high potential resource of biomass energy in rural areas especially in south east Asia. However, regarding biomass energy gathering stable amount of biomass resources is one of problems when we apply biomass energy as a baseline energy resource as biomass resources from forest is depending on season and climate. About this problem, it can be soleved if we can utilize waste from industries as biomass fuel because waste can generate stably and not depend on nature. Moreover, it contributes to make additional sales for industries that has high potential in rural areas.

Our research focused on waste from palm oil industries in Malaysia. Malaysia is the 2nd biggest country of palm oil production only after Indonesia.

In the production process of palm oil, three types of biomass. Empty Fruit Bunch (EFB), Kernel Shell (KS) and Mesocarp Fiber (MF), shown in Fig. 28.1, are produced as wastes. In the actual case, many palm oil mills utilize only MF as fuel for internal electricity generation and other biomass are just thrown away as they can get enough amount of electricity by utilizing MF.

Fig. 28.1 Three type of biomass waste from palm oil mills

Table 28.1 Characters of waste from palm oil mills

	Calorific value (kcal/kg)	Moisture contents (%)	Generating rate from fresh fruit bunch (%)
Empty Fruit Bunch	9666	49.9	22.0
Kernel Shell	9081	48.7	5.5
Mesocarp Fiber	10083	50.0	13.5

However, these wastes have pros and cons to be utilized as biomass fuels. About pros, we can get stable amount all the year. Also exhaust from burning waste has low NOX and SOX. About cons, these have high moisture content and low energy density. Moreover, each biomass has different characters as described Table 28.1 (Malaysian palm oil board 2017).

28.2 Objectives

We focus on these three kinds of biomass and conduct the economic assessment on utilizing each combination of three biomass not only for internal electricity generation but also for selling local area via the grid.

Objective of our study is showing a feasibility of utilizing wastes from palm oil mills and how much potential sales they can get from selling electricity to grid by generating electricity.

28.3 Methodology

28.3.1 Model of Calculation

We used seven cases below for calculation. These are distinguished by what kinds of biomass is utilized in every combination of three biomass.

Case 1 Utilizing all biomass
Case 2 Utilizing EFB and MF
Case 3 Utilizing EFB and KS
Case 4 Utilizing MF and KS
Case5 Utilizing only EFB
Case 6 Utilizing only MF
Case 7 Utilizing only KS.

The model of system is shown in Fig. 28.2. Utilized biomass is for generating electricity by using a boiler and a turbine. Ash is also produced from a boiler. Cases utilizing EFB (case 1, 2, 3, 5) need pretreatment process for EFB. Pretreatment

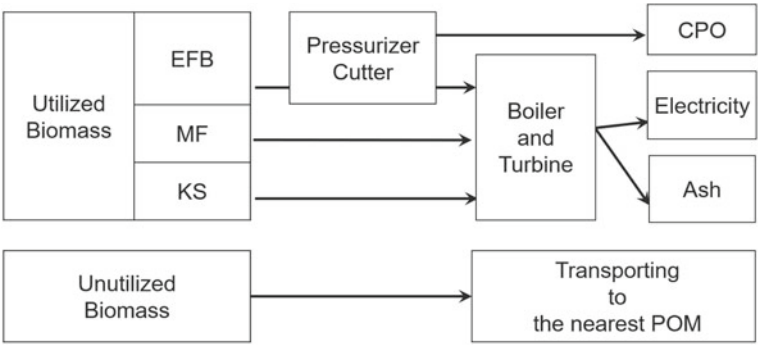


Fig. 28.2 The system of waste to electricity

system consists of a pressurizer and a cutter. From this pretreatment, we will get crude palm oil (CPO). Unutilized biomass is transferred to the nearest palm oil mill.

About techno-economic assessment, we calculated annual cost and sales from this system in each case. In cost part, we calculated construction cost of facilities (a boiler, a turbine, a pressurizer, a cutter), running cost (operating and maintenance) and transportation cost. About sales part, we calculated sales from selling electricity, ash and also CPO from pretreatment of EFB.

28.3.2 Cost Calculation

Construction cost (CC) is calculated according to the following formula. It depends on plant cost (PC) and an expense rate (ER). And also when EFB is utilized, cost of treatment facilities is included into the number of PC.

$$\mathrm{CC} = \mathrm{PC} \times \mathrm{ER}$$

Plant cost depends on its capacity size. However, its not be directly proportional the size of capacity and follows 0.7 power law because of economies of scale so plant cost can be calculated according to the following formula. (Yu et al. 2008) We use 25 million JPY as the reference price of 400 kW capacity of energy facilities (a boiler and a turbine) in Indonesia. The reference price of treatment facilities is 1260000RM for 22.8t/h capacity.

$$PC = PC' \times \frac{(CAP)}{(CAP)'} 0.7$$

PC Plant cost
PC′ Reference plant cost

CAP Capacity of the plant
CAP′ Capacity of the reference plant.

Capacity of the plant is decided from which biomass are utilized as fuel and each amount and calorific value (CV) and also this capacity is regard energy efficiency (GE) of a boiler and a turbine. We used data shown in Table 28.1 and assume energy efficiency to be 20%.

$$\mathrm{CAP} = \mathrm{GE} \sum_{\mathrm{n}}^{(\mathrm{EFB,MF,KS})} \mathrm{CVn} * \mathrm{BQn}$$

n EFB, MF, KS (depending each case)
GE Energy efficiency
CVn Calorific Value of n
BQ Biomass Quantity.

Expense rate (ER) depends on rate of interest and life time of a plant. We assumed 6% interest rate and 16 year plant life time based on previous study (Yu et al. 2008).

$$\mathrm{ER} = \frac{\mathrm{R}}{1 + (1 + \mathrm{R})^{\mathrm{N}}}$$

R Interest rate
N Plant life time.

About running cost (RC), we assumed it's 2% of the plant cost as it depends on the size of plant roughly. About transportation cost (TC), we used the following formula.

$$\mathrm{TC} = (\mathrm{TCA} * \mathrm{D} + \mathrm{TCR}) * \mathrm{UBQ}$$

TCA depending on distance
TCR not depending on distance
D distance to the nearest plant
UBQ unutilized biomass quantity.

TCA is a coefficient of transportation cost depending on distance and quantity of loads and we put 5JPY/km*t. TCR is also a coefficient of transportation cost not depending on distance but depends on quantity of loads and we put 2500 JPY/t. (Yu et al. 2008) About distance to the nearest plant, we assumed from actual map to be 30 km.

Summarizing the above, total cost is calculated according to the following formula.

$$\mathrm{COST} = \mathrm{CC} + \mathrm{RC} + \mathrm{TC}$$

Table 28.2 FIT price of biomass energy in Malaysia

Capacity	Selling price (RM/MWh)	Application period
Up to and including 10 MW	308.5	16 years
above 10 MW and up to and including 20 MW	288.6	
above 20 MW and up to and including 30 MW	268.7	

28.3.3 Selling Price of Electricity in Malaysia

There is feed-in tariff (FIT) in Malaysia regarding biomass energy. Each selling price of electricity is decided from FIT referring Table 28.2. (Tenaga National 2018)

However, FIT can be applied only until 30 MW capacity. About a plant generating electricity over 30 MW, selling price of electricity is general price. We assumed general price of electricity from market price to be 200RM/MWh.

About internal electricity consumption, we used 0.2 MWh per production of CPO from 1ton fresh fruit brunch. Amount of selling electricity also depends on net thermal efficiency assumed it to be 88% and working time rate of palm oil mill assumed to be 85%. According the above, sales from selling electricity can be calculated by the following formula.

$$\mathrm{EP} = \mathrm{EPRICE} \times \mathrm{EE} \times (\mathrm{CAP} - \mathrm{IC}) \times 365 \times 24 \times \mathrm{WT}$$

EP	sales from selling electricity
EPRICE	Electricity price
IC	Internal electricity consumption
WT	working time rate.

28.3.4 Selling Price of Ash as Fertilizer

Ash from firing waste from palm oil mill have active ingredents (Urea, Cirp, Mop, Kieserite) as a fertilizer. Amounts of active ingredients from each waste are shown in Table 28.3. Market price of fertilizer of these active ingredients is shown in Table 28.4. From these data, we assessed each price of ash as a fertilizer from market price of pure active ingredents and the result is shown in Table 28.5 (Yasuo 2003).

Table 28.3 Amount of Active ingredient of fertilizer From each Biomass (kg/t)

	EFB	MF	KS
Urea	7.54	6.93	75.0
Cirp	1.61	5.03	16.1
Mop	4.54	0.368	1.70
Kieserite	1.75	8.16	56.5

Table 28.4 Market price of fertilizer

	Price (RM/t)
Urea	335
Cirp	280
Mop	580
Kieserite	400

Table 28.5 Assumed price of ash from each biomass

	Price (RM/t)
EFB	36.4
MF	7.21
KS	53.2

According to the above prices, sales from selling ash can be calculated in the following fomula.

$$AP = \sum_{n}^{(EFB,MF,KS)} (AVn * BQn \times 365 \times 24 \times WT)$$

AP: Selling price of ash
AVn: Ash price as fertilizer of n.

28.3.5 Sales Calculation

Total sales consists of total selling price of electricity, total selling price of ash and sales from CPO from treatment of EFB in the cases that utilize EFB. Sales from CPO from treatment of EFB can be calculated in the following formula. We assumed the rate of generating CPO from EFB treatment to be 0.24% and market price of CPO to be 1000RM/t.

$$CPOP = CRE * EFBQ * CPRICE \times 365 \times 24 \times WT$$

CPOP Sales from CPO from treatment of EFB
CRE CPO rate from EFB
EFBQ EFB quantity
CPRICE Market price of CPO.

Summrizing all formulas about sales, total sales is according to the following formula.

$$SALES = EP + AP(+CPOP)$$

28.3.6 Profit Calculation

In conculution of calculation, profit is just difference between sales and cost. We conducted economic assessment for different size of palm oil mills in each case. Minimam capacity of FFB treatment is 10 t/h and we calculated at each capacity increased by 10t/h umtil 100t/h.

28.4 Result

28.4.1 Cost Calculation

Cost calculation The result of construction cost is shown in Fig. 28.3. It discrives that the initial cost of case 6 which is the common system of the actual situation (only MF is utilized) is the lowest.

The result of transportation cost is shown in Fig. 28.4. In this figure, transportation cost in each case at the palm oil mill whose capacity is 50t/h. From result of both

Fig. 28.3 Construction cost

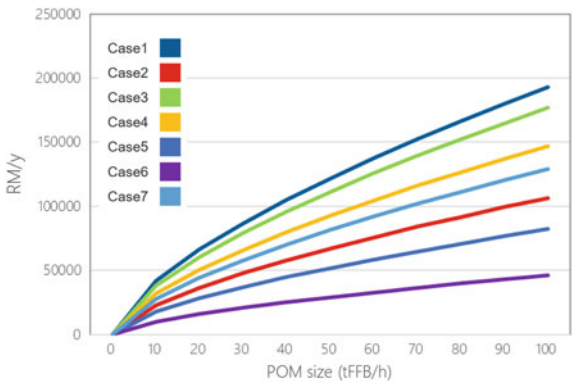
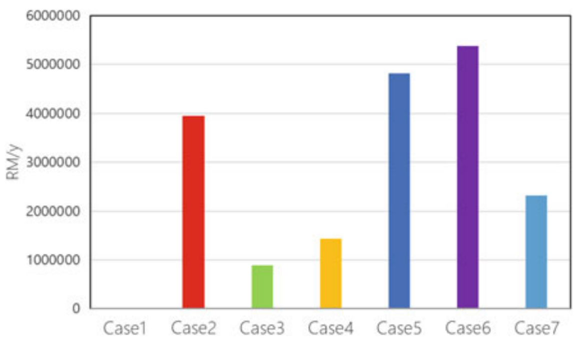


Fig. 28.4 Transportation cost (at 50 h/t palm oil mill)



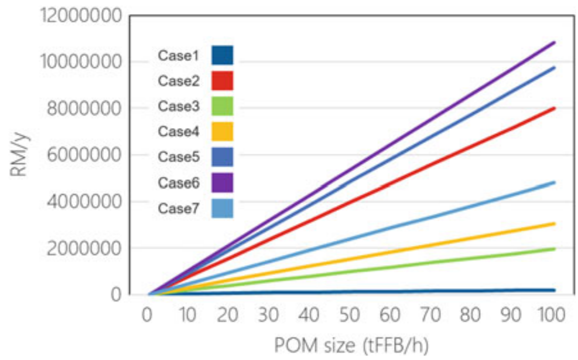


Fig. 28.5 Total cost

construction cost and transportation cost, whether utilizing KS or not, it spend much cost treat KS compared with other biomass. However, utilizing KS is cheaper than transporting KS.

The calculation of total cost is shown in Fig. 28.5. As a result, transportation cost has high influence about total cost. Eventhough intial cost of case 6 is lowest, it will spend highest cost in total so from long term perspective case6 can not be best case. However, it has no influence about orders when the distance of nearest palm oil mill is two times bigger.

28.4.2 Sales Calculation

At first, the result of calculation of generating electricity is shown in Fig. 28.6. It describes that the order of high quality as solid fuel is KS, EFB, MF. When the size of all palm oil mills in Selangor is 50t/h and case1 applied into that situation, it will generate the amount of electricity as much as 26% of electricity generation from the power plant of Genting Sanyen Power Sdn. Bhd. in Selangor (Suruhanjaya Tenaga 2010).

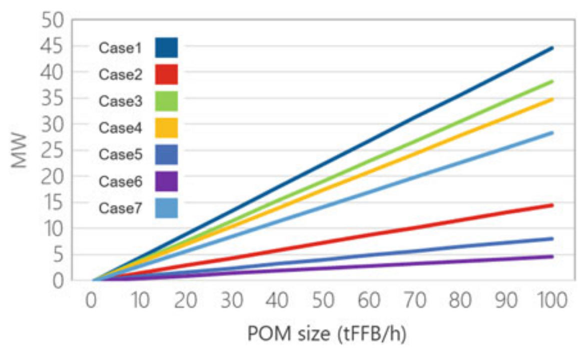


Fig. 28.6 Electricity generation

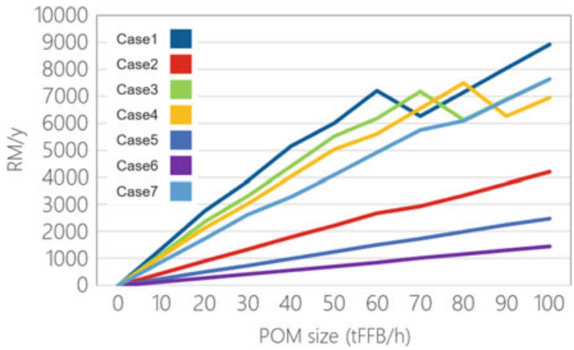


Fig. 28.7 Sales from selling electricity

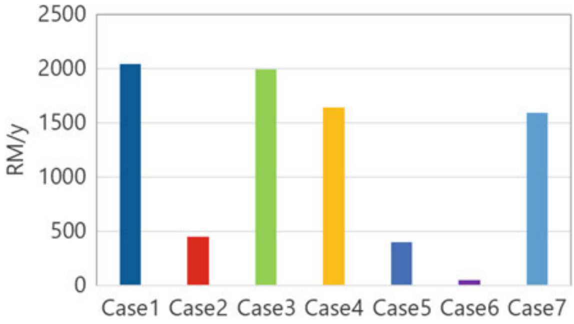


Fig. 28.8 Sales from selling ash (at 50t/h palm oil mill)

However, sales from selling electricity is highly depends on whether FIT can be applied or not. We can see from Fig. 28.7 that profit is decreased when FIT cannot be applied.

The result of selling price of ash is shown in Fig. 28.8. It describes that the order of quality of ash as fertilizer is also same order with the one of solid fuel, and KS, EFB, and MF.

As shown in Fig. 28.9, compared with total sales, sales from selling ash and CPO from treatment of EFB have no influence to the result of calculation. So, the result of total sales is mostly similar with the result of sales from selling electricity.

28.4.3 Profit Calculation

As a result, total cost is dramatically smaller than total sales in every case. As shown in Fig. 28.10, the calculation result of profit is also highly influenced by applying FIT. Moreover, the best case is changed depending on size of palm oil mill.

The case 1 drops from the largest profit because of inapplicability of the Malaysian FIT price of its over capacity beyond 30 MW.

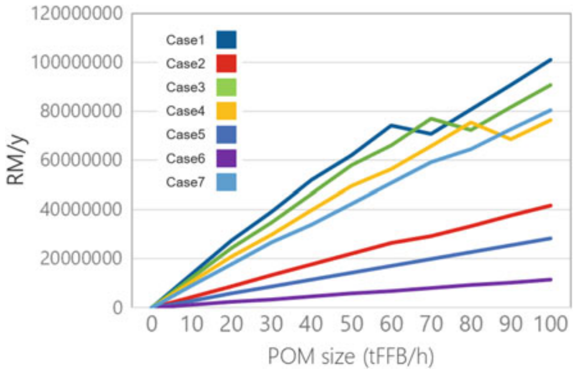


Fig. 28.9 Total sales

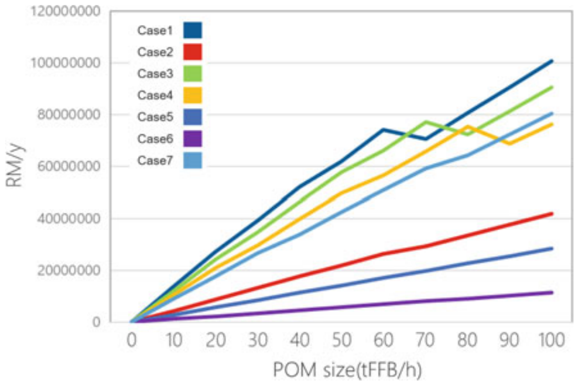


Fig. 28.10 Total profit

28.5 Conclusion

We clarified that (1) the transportation cost shared largest among all the cases, (2) power is the largest among the three sales components, and (3) the case 1 utilizing all the biomass wastes shows generally largest profit while the case 6 commonly used recently indicates least among the cases.

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Chapter 29
Influence of Thermal Conductivity and Subsurface Temperature on Life-Cycle Environmental Load of the Ground Source Heat Pump in Bangkok, Thailand

Yutaro Shimada, Youhei Uchida, Hideaki Kurishima, and Koji Tokimatsu

Abstract The aim of this study is to evaluate the life-cycle environmental load of a ground source heat pump (GSHP) in Bangkok, Thailand. We conducted a life-cycle inventory analysis based on the assumption of the introduction of an optimally-designed GSHP to a commercial facility in Bangkok, Thailand. An air source heat pump (ASHP) was selected as a comparison target. Moreover, sensitivity analysis was conducted based on thermal conductivity and subsurface temperature to clarify the influence of changes in groundwater flow and subsurface temperature. Indicators of analysis were the life-cycle CO_2, NO_X, and SO_2 (LC–CO_2, LC–NO_X, and LC–SO_2, respectively) emissions. As a result, the LC–CO_2, LC–NO_X, and LC–SO_2 emissions of GSHP were reduced by 27.8%, 24.8%, and 25.6%, respectively compared with ASHP. The LC–CO_2 emissions of GSHP within the scope of sensitivity analysis were reduced by 26 to 28.6% compared with ASHP. These results show the GSHP in Bangkok could achieve smaller environmental load than the ASHP and the changes in groundwater flow and subsurface temperature do not greatly influence on the life-cycle environmental load. However, this study indicated that the large ground heat exchanger is required compared to the other areas, e.g., United Kingdom, and China. This means the economical and space constraints would be the barrier of introduction of GSHP in Bangkok. Therefore, further research is required to evaluate not only the environmental aspect, but also the economic aspect.

Keywords Ground source heat pump · Life-cycle inventory analysis · Thailand · Sensitivity analysis

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29.1 Introduction

In Thailand, where economic development continues, energy demand is expected to increase in the future. The fuel used for power generation in Thailand is 64% for natural gas and 18% for coal. In the future, the Thai government plans to reduce the proportion of natural gas and increase the proportion of coal (Electricity Generating Authority of Thailand Electricity Generating Authority of Thailand 2017). Therefore, the deployment of high efficiency equipment is urgently required to reduce greenhouse gas emissions and mitigate air pollution in Thailand. Among the electricity consumers, air conditioner accounts for a large portion of total electricity consumption, owing to the large demand for cooling. For instance, approximately 60% of electricity in commercial buildings are consumed for air conditioning (Chirarattananon and Taweekun 2003). Therefore, the deployment of high efficiency air conditioning system will play an important role for reducing greenhouse gas emissions such as CO_2, NO_X and air pollutant emissions such as SO_2.

A ground source heat pump (GSHP) has been known as the one of the high efficiency air conditioning system in general. Although GSHP had been considered as not appropriate for the tropics because of their high subsurface temperature, a geological survey clarified the subsurface temperature in Chao Phraya Plain is lower than the atmospheric temperature within the depth of 20–50 m. Therefore, GSHP in this plain could have potential to achieve high efficiency, even in the tropics (Yasukawa et al. 2009). Based on this survey, a pilot study of GSHP in Bangkok was conducted to verify its potential in comparison to the conventional system, i.e., an air source heat pump (ASHP). As a result of the pilot study, GSHP could reduce electricity consumption by 30% from that of ASHP (Chokchai et al. 2018).

The pilot study was conducted in a small room with a total floor area of 15 m^2. However, when considering the deployment of GSHP in the tropics, it is vital to evaluate their performance in a large-scale facility, such as a super market.

Moreover, as GSHP in this plain requires construction work for embedding heat-exchange pipes to the subsurface until the depth of 50 m, it is essential to evaluate not only the environmental load during the operation stage but also during the entire life-cycle stage.

Several studies on life-cycle assessment (LCA) of GSHP have been carried out in the United Kingdom, China, and Japan. The LCA study in United Kingdom was performed to clarify the environmental performance of GSHP over gas boilers (Greening and Azapagic 2012). In the case of China, the LCA study was performed based on the experimental data to clarify the changing in the environmental performance depending on the material of the ground heat exchanger (Ren et al. 2018). In the case of Japan, the LCA study was carried out assuming introduction to a residential house in Sapporo city, northern part of Japan (Nagano et al. 2006). In each case, detailed analysis was performed based on the actual data.

However, except in the case of Japan, few studies have been found where an LCA has been performed by designing a ground heat exchanger that is optimal for the building size, cooling load, and taking regional characteristics into consideration.

Here, regional characteristics refer to meteorological conditions, thermal conductivity and subsurface temperature. Given that the size of ground heat exchanger affects the environmental load during the manufacturing and installation stages, it is essential to conduct the LCA based on the optimal design of ground heat exchanger in order to evaluate the life cycle environmental load properly.

Generally, rich groundwater flow enhances thermal conductivity (Shrestha et al. 2015), and GSHP's efficiency is highly affected by thermal conductivity and heat source temperature, i.e., subsurface temperature (Yasukawa et al. 2009; Safa et al. 2015). Therefore, clarifying the influence of changes in thermal conductivity and subsurface temperature on the life-cycle environmental load are important to verify an environmental performance of GSHP in Bangkok under the various groundwater flow and subsurface temperature conditions.

29.2 Objective

The objectives of this research are to conduct life-cycle inventory and sensitivity analysis for the installation of a GSHP system with an optimally-designed ground heat exchanger in a commercial building, such as a super market, in Bangkok, Thailand. The goals of life-cycle inventory analysis are to calculate the life-cycle CO_2, NO_X, and SO_2 (LC–CO_2, LC–NO_X, and LC–SO_2, respectively) emissions. The parameters of sensitivity analysis are the thermal conductivity and subsurface temperature.

29.3 Methodology

29.3.1 Simulation of Cooling Load

"The Best Program" (Hasegawa et al. 2017) was used to design an architecture model of a commercial building and calculate the hourly annual cooling load. The architecture model is a square of 40 × 40 m with two floors at a floor-to-floor height of 7 m. Thus, the total floor area of the architecture model was 3200 m^2. Each floor has a perimeter zone and an interior zone. The perimeter zone was an area up to 5 m inside from the outer wall, and the other area were treated as interior zone.

The annual cooling load was calculated by inputting the architecture model, air conditioner operation schedule, and "EnergyPlus" weather data in Bangkok (EPW weather data) (Crawley et al. 2000) into "The Best Program". The operation schedule was set at 365 days per year and 8:30–22:30 (14 h per day) in accordance with typical supermarkets in Thailand. Moreover, the room temperature and relative humidity were set at 26 °C and 50%, respectively.

Table 29.1 shows the specifications of architecture model and cooling load simulation results.

Table 29.1 The specifications of architecture model and simulation cooling load

Purpose of building		Supermarket
Building area (m^2)		1600 (Square shape)
Number of floors		2
Total floor area (m^2)		3200
Height of building (m)		14
U-Value (W/m^2K)	Outer wall	1.04
	Ceiling	1.30
	Roof	0.63
	Floor	1.30
Cooling load	Maximum (kW)	426
	Annual average (kW)	231
	Annual (MWh)	1180

29.3.2 System Designing and Electricity Consumption

In order to predict the energy consumption during the operation stage, the annual electricity consumption load was calculated per hour using the "GroundClub" simulation software for GSHP (Nagano et al. 2006; Katsura et al. 2008).

An ASHP was selected as the comparison target, and its annual electricity consumption load was calculated by "GroundClub". Table 29.2 shows the specifications of GSHP and ASHP considered in this research.

The type of ground heat exchanger was the closed loop type with double U-tube. The total length of ground heat exchanger (heat exchange well) was designed so that the 90th percentile value of the heat pump inlet water temperature was 38 °C or less, as that of atmospheric temperature was approximately 33 °C (Crawley et al. 2000). This is based on the finding that the efficiency of a water source heat pump exceeds that of an air source heat pump when the heat pump inlet water temperature exceeds the atmospheric temperature by 5 °C (Yasukawa et al. 2009). The depth of each wells was set at 50 m based on the geological survey (Yasukawa et al. 2009).

Table 29.2 The specifications of the GSHP and ASHP

Type of heat pump	GSHP	ASHP
Heat pump rated cooling COP	4.5	2.4
Calculated system COP	2.9	1.98
Type of ground heat exchanger	Double U-tube	–
Total length of the ground heat exchanger (m)	12,500	–
Subsurface temperature (°C)	28	–
Ground thermal conductivity (W/mK)	1.82	–
Ground heat capacity (kJ/m^3K)	2600	–

The rated coefficients of performance (COP) of GSHP and ASHP were determined using a technical data book of the manufacturer. Furthermore, the thermal conductivity value was set at 1.82 W/m·K based on the result of the thermal response test (TRT) conducted in Bangkok (Uchida and Fujii 2018). The subsurface temperature was set at 28 °C based on the hearing investigation to the pilot study research group (Chokchai et al. 2018).

According to the simulation, the annual electricity consumption load of GSHP was approximately 400 MWh, while that of ASHP was approximately 600 MWh. Therefore, the annual electricity consumption load of GSHP was 33% lower than that of ASHP.

29.3.3 Life-Cycle Inventory Analysis

Life-cycle inventory analysis was conducted following the guidelines for the life-cycle assessment of GSHP (Ministry of the Environment, Japan 2012).

The functional unit was set as one-year's operation of heat pump on the architecture model which was designed at the "3.1 simulation of cooling load".

The system boundary was set as the entire life-cycle, from the manufacturing to the disposal stages. Figure 29.1 shows the system boundary of life-cycle inventory analysis. The installation stage of ASHP did not include the construction material manufacturing, waste transportation, and waste intermediate treatment processes, since those processes were assumed to be occurred during the construction of ground heat exchanger.

The lifetime of ground heat exchanger was set at 50 years, and that of other equipment was set at 20 years. The operation period of GSHP was set at 50 years in accordance with the lifetime of ground heat exchanger. On the other hand, the operation period of ASHP was set at 20 years.

The process data list which are required for the analysis were determined by following the guidelines (Ministry of the Environment, Japan 2012). The process data list and data source are shown in Table 29.3. Each process data was set as the amount of one-year in accordance with the functional unit. All equipment materials were the latest models as of 2017, and it was assumed that those manufactured in Japan were used in Thailand.

IDEA v2 (National Institute of Advanced Industrial Science and Technology, Japan Environmental Management Association for Industry 2017), inventory database for LCA in Japan, which was replaced with the power supply configuration in Thailand, was used for background data.

Lastly, LC–CO_2, LC–NO_X, and LC–SO_2 were obtained from multiplying the process and foreground data.

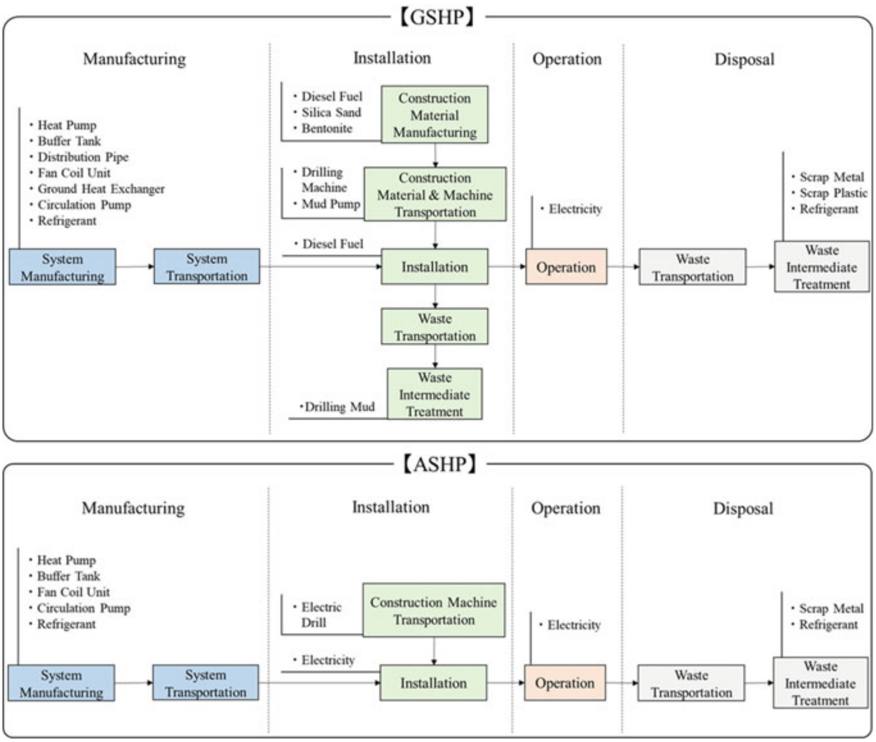

Fig. 29.1 The system boundary of life-cycle inventory analysis

29.3.4 Sensitivity Analysis

The parameters of sensitivity analysis were "Thermal Conductivity" and "Subsurface Temperature". The ranges of each parameter were determined based on a literature review.

The geologic column at the pilot study site described that subsurface soil in the central area of Bangkok consisted of mainly clay and sand (Chokchai et al. 2018). Thermal conductivity of saturated clay and sand are in the range of approximately 1.0–1.5 W/m·K (Hokkaido University geothermal utilization system engineering course 2007). In case that the heat advection effect caused by the groundwater flow can be expected, thermal conductivity was approximately twice as high as that without the heat advection effect (Sakata et al. 2017). Based on above discussion, we set the parameter of thermal conductivity as the range of 1.0–3.0 W/m·K.

According to a geological survey of Chao Phraya Plain, subsurface temperature in whole Chao Phraya Plain at the depths between 20 and 50 m ranged from 27.8 to 31.5 °C (Yasukawa et al. 2009). Based on the result from the survey, subsurface temperature was set as the range of 28.0–31.0 °C.

Table 29.3 The process data list and data source

System boundary		List	Data source
Major	Minor		
Manufacturing	System manufacturing	Heat pump	KHT150, KOBE STEEL, LTD. and RUA-UP511, Toshiba Carrier Corporation
		Buffer tank	AST-175 V, Hitachi Metals, Ltd.
		Distribution pipe	GUP-25AN60, INOAC Housing & Construction Materials Co.,Ltd.
		Fan coil unit	FWMF12FET(Z), DAIKIN INDUSTRIES, Ltd.
		Ground heat exchanger	The data retrieved from the report of Ministry of the Environment, Japan
		Circulation pump	80 × 65FSGD57.5E, EBARA CORPORATION.
		Refrigerant	Chlorofluoromethane
	System transportation	Heat pump	Transport distances of 200 km
		Buffer tank	
		Distribution pipe	
		Fan coil unit	
		Ground heat exchanger	
		Circulation pump	
		Refrigerant	
Installation	Construction material manufacturing	Diesel fuel	Hearing investigation to the pilot study research group
		Silica sand	Calculated based on the structure of the ground heat exchanger
		Bentonite	The data retrieved from the report of Ministry of the Environment, Japan
	Construction material & machine transportation	Diesel fuel	Transport distances of 200 km
		Silica sand	
		Bentonite	

(continued)

Table 29.3 (continued)

System boundary		List	Data source
Major	Minor		
		Drilling machine	Hearing investigation to the pilot study research group, transport distances of 200 km
		Mud pump	
	Installation	Diesel fuel	–
	Waste transportation	Drilling mud	Transport distances of 200 km
	Waste intermediate treatment	Drilling mud	Calculated based on the structure of the ground heat exchanger
Operation		Electricity	Simulation result from "3.2 System designing and electricity consumption"
Disposal	Waste transportation	Scrap metal	
		Scrap plastic	Transport distances of 200 km
		Refrigerant	
	Waste intermediate treatment	Scrap metal	Heat pump, buffer tank, fan coil unit and circulation pump
		Scrap plastic	Distribution pipe and ground heat exchanger
		Refrigerant	—

After determining the ranges of the sensitivity analysis parameters, the heat pump inlet water temperature was simulated using "GroundClub" to determine the total length of the ground heat exchanger. The total length of the ground heat exchanger was optimally designed so that the 90th percentile value of heat pump inlet water temperature did not exceed 38 °C, which is the same standards as in "3.2 system designing and electricity consumption". Table 29.4 shows the total length of ground heat exchanger corresponding to the parameters of thermal conductivity and subsurface temperature. The total length of ground heat exchanger decreases as thermal conductivity increases, and increases as subsurface temperature increases.

Lastly, the process data related to the ground heat exchanger were modified to be proportional to the total length of ground heat exchanger to recalculate the LC–CO_2 emissions.

Table 29.4 Settings of the total length of the ground heat exchanger in sensitivity analysis

Ground thermal conductivity (W/mK)	Subsurface temperature (°C)	Total length of the ground heat exchanger (m)
1	28	16,500
2	28	12,000
3	28	10,300
1.82	28	12,500
1.82	29	14,000
1.82	30	15,500
1.82	31	17,500

29.4 Results and Discussion

29.4.1 Life-Cycle Inventory Analysis

Figure 29.2 shows the LC–CO_2, LC–NO_X, and LC–SO_2 emissions. The LC–CO_2, LC–NO_X, and LC–SO_2 emissions of GSHP were reduced by 27.8, 24.8, and 25.6%, respectively compared with ASHP. As GSHP has a ground heat exchanger, the environmental loads of manufacturing and installation stages were larger than those of ASHP. However, the environmental load during the operation stage of GSHP accounted for 85–90%, so the life-cycle environmental load of GSHP was smaller than that of ASHP.

The CO_2 emissions during the operation stage of GSHP accounted for 90% of the LC–CO_2 emissions. In LCA studies of GSHP in United Kingdom, China, and Japan, the CO_2 emissions during the operation stage of GSHP accounted for 95, 99, and 90% of the LC–CO_2 emissions, respectively (Greening and Azapagic 2012; Ren et al. 2018; Nagano et al. 2006). Therefore, it was shown that GSHP in Bangkok had larger ratio in environmental load during the manufacturing and the installation stage than GSHP in United Kingdom and China. This implies that GSHP in Bangkok requires large ground heat exchanger compared to the United Kingdom and China.

In the case of Japan, GSHP is assumed to be introduced to residential house with the total floor area of 130 m^2 in Sapporo city, Japan. The scale of building in the study and the cooling load during summer season in Sapporo city are small. On the other hand, Bangkok has a large cooling load throughout the year, and the scale of building to be introduced in this study is greatly larger than that in the case of Sapporo City. Therefore, it is difficult to make a comparison between the case of Sapporo city, Japan and that of Bangkok, Thailand.

However, except in the case where the conditions such as the scale of facility and the weather conditions are largely different, GSHP in Bangkok is presumed to require large ground heat exchanger compared to the other areas.

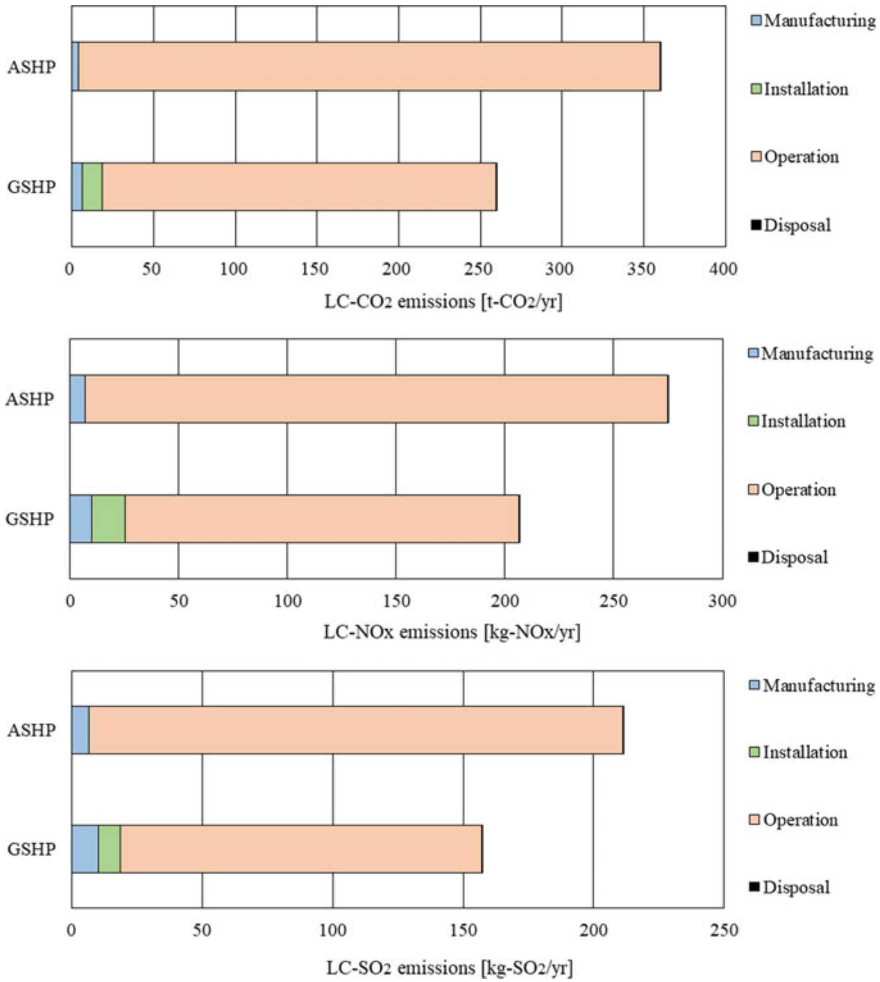

Fig. 29.2 LC–CO_2, LC–NO_X, and LC–SO_2 emissions of GSHP and ASHP

29.4.2 Sensitivity Analysis

Figure 29.3 shows the result of sensitivity analysis based on thermal conductivity and subsurface temperature. The LC–CO_2 emissions of GSHP were reduced by 26–28.6% compared with ASHP within the scope of sensitivity analysis. Although the LC–CO_2 emissions were increased in response to the increasing in the total length of the ground heat exchanger, the changes in those were slight.

The electricity consumption in the operation stage of every condition were almost equal, since the ground heat exchanger were designed so that the 90th percentile value of the heat pump inlet water temperature was not exceeding 38 °C. This indicates

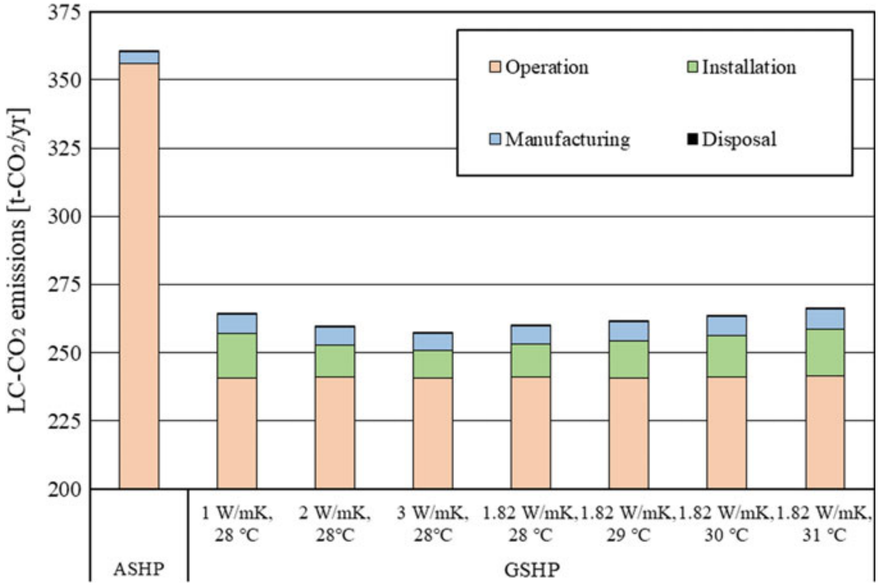

Fig. 29.3 The sensitivity analysis of LC–CO_2 emissions

that the environmental loads during the operation stage are almost constant in every condition. The operation stage accounts for approximately 90% of the life-cycle environmental load. Therefore, even if the environmental load which accounts for the remaining 10% increases slightly, the impact on the life-cycle environmental load is small. That is, changes in groundwater flow and subsurface temperature did not greatly influence on the life-cycle environmental load.

29.5 Conclusion

This study conducted a life-cycle inventory analysis based on the assumption of the introduction of optimally-designed GSHP to the commercial facility in Bangkok, Thailand. ASHP which are known as a conventional cooling system was selected as a comparison target. Indicators of analysis were the LC–CO_2, LC–NO_X, and LC–SO_2 emissions.

Sensitivity analysis were also conducted based on the thermal conductivity and subsurface temperature which are fundamental elements for the heat exchange performance.

As a result, the LC–CO_2, LC–NOx, and LC–SO_2 emissions of GSHP were reduced by 27.8, 24.8, and 25.6%, respectively compared with ASHP. The main reason for this is that the electricity consumption during the operation stage of GSHP is lower than that of ASHP. Within the scope of sensitivity analysis, the LC–CO_2 emissions of GSHP were reduced by 26 to 28.6% compared with ASHP. That is, changes in groundwater flow and subsurface temperature did not greatly influence on the life-cycle environmental load. These results indicate that the introduction of GSHP to Bangkok would reduce the environmental load.

However, the environmental load of the manufacturing and installation stage in this study accounted for larger portion than that in the other areas, e.g., United Kingdom and China. This indicated that GSHP in Bangkok requires large ground heat exchanger compared to these areas. For instance, under the conditions of this study, the space for the installation of ground heat exchanger was approximately twice as the total floor area of building. Since there are barriers in terms of the space and economic constraint, the installation of optimally-designed ground heat exchanger in this study are difficult to realize.

Therefore, for the future research of GSHP in Bangkok, not only the environmental assessment, but also the economic assessment will be vital based on the combined operation with ASHP and on the optimally-designed ground heat exchanger.

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Chapter 30
Material Criticality Assessment for Business Purposes Using Fuzzy Linguistic Method

Xiaobo Chen, James Goddin, and Jacquetta Lee

Abstract A secure supply of raw materials plays a vital role in the rapid growth of emerging technologies. The criticality assessment has been introduced to evaluate the supply risk of materials from economic, social and environmental aspects. From business perspective, multiple critical metrics should be involved, so that the decision makers can focus on the different metrics and put efforts to minimize the corresponding risks. However, due to the complexity of assessment and uncertainties in data sources, some metrics cannot be evaluated quantitatively, but qualitatively. This paper introduces a fuzzy linguistic approach to evaluate multiple risk metrics for material criticality assessment. The risk levels and the importance weight of metrics, expressed in linguistic terms, are modeled by triangular or trapezoid membership functions. We apply this method to evaluate the criticality of three materials: Cobalt, Tungsten, and Yttrium. We use matrix operation to aggregate the MFs of the multiple metrics in order to represent the overall criticality. As a result, the three materials are ranked according to their critical levels. The proposed fuzzy linguistic approach shows the advantage to evaluate the criticality with multi-criteria when only qualitative data is available. The membership function is an appropriate way to represent linguistic terms with imprecision, which are commonly used to interpret risk terms. The definition of multiple metrics provides flexibility for the users to choose risk categories they are interested in, and the aggregation of the metrics supports them to compare the criticality of materials. Further study may focus on how to justify importance weight judgments to make tradeoff decision, or integrate temporal factor to predict the future critical risk for business purpose.

Keywords Material criticality · Fuzzy linguistic method · Multi-criteria aggregation

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30.1 Introduction

The ever increasing consumption of raw materials has led to concern about future supply in terms of both total requirements for raw materials and their impacts on economy, society and environment. Forced by the fast development of technology, demands for raw materials have rapidly grown. However, the material supply cannot meet this increasing demand in global market (Rosenau-Tornow et al. 2009). Therefore, a secure supply of raw materials becomes a critical issue that influences all the stakeholders through supply chain. There have been numerous studies to develop rigorous and comprehensive methodologies for assessing material criticality. For example, a criticality matrix approach, developed by the U.S. National Research Council (National Research Council 2008), defines two indicators: supply risk and economic importance and plots them against each other in the form of risk-matrix to classify the critical levels (e.g., more critical, less critical) of materials. The European Commission applied this approach only to separate "critical" and "non-critical" materials through fixed thresholds defined by the Ad hoc Working Group on Defining Critical Raw Materials, appointed by the EU (Commission 2014). Whilst this approach was based on the two-dimensional matrix approach, a third dimension of "environmental implications" was added to quantify the environmental impacts to human health and the ecosystem (Graedel et al. 2012; Nassar et al. 2012). To simplify the comparison of criticality of different materials, the authors also applied a weighting approach to aggregate indicators to obtain a single overall criticality score. Several studies have reviewed different approaches for criticality assessment, and found out although most of criticality assessment studies evaluate supply risk, economic vulnerability, even environmental implications in common, the choices of indicators and weighting approaches varies considerably and are arbitrarily determined by the different stakeholders (e.g., private companies, industrial sectors and governmental organizations) (Erdmann and Graedel 2011; Achzet and Helbig 2013; Glöser et al. 2015; Lloyd et al. 2012). This diversity is necessary to meet the perspectives and needs of the different stakeholders, but makes it difficult to reach a consensus in respect of the results calculated.

The quantification of criticality indicators requires reliable and specific data. Although various data sources and approaches can be considered for data acquisition, for example, Life Cycle Assessment databases are generally used to calculate the environmental impacts (Mancini et al. 2015; Hatayama and Tahara 2018), a rigorous, transparent and accurate calculation for both indicators is still questionable due to the complexity of assessment and the extensive effort for data acquisition. Where experts have difficulty in providing an exact numerical value to express their opinions, linguistic assessment is a more realistic alternative (Duclos et al. 2010; Goddin 2019; Chuu 2011). In this way, the risk metrics regarding criticality can be measured as linguistic terms, such as "*low*", "*medium*" and "*high*" and so on. However, the use of such linguistic terms introduces uncertainty due to verbal subjectivity, named as linguistic imprecision (Druzdzel 1989). This is because linguistic terms are usually based on subjective judgments which contain imprecise, ambiguous or vague expressions. Moreover, when multiple metrics are considered to assess the overall criticality, the linguistic terms are difficult to be directly aggregated into a single term. Although the single rating number is usually assigned to each term for aggregation purposes (Duclos et al. 2010), it ignores or loses information about linguistic imprecision. In response to these limitations, a fuzzy linguistic approach has been developed based on fuzzy set theory (Zadeh 1975; Zadeh 1965) as a way to represent imprecise, incomplete or vague information (Bosc and Prade 1997; Dubois and Prade 1998). This approach has already been used in different fields to evaluate the supply chain flexibility (Chuu 2011), the performance of products (Cheng and Lin 2002), the quality of information (Herrera-Viedma et al. 2006) and so on. These studies suggest that the fuzzy linguistic approach can represent appropriately the linguistic terms and capture imprecise information for supporting decision-making processes. This study has two objectives:

(1) Investigate the risk metrics for criticality assessment at a business level;
(2) Develop appropriate approach to manage linguistic information.

Therefore, in this paper, we explore the fuzzy linguistic approach to represent directly linguistic information from experts' knowledge, which are used for qualitative criticality assessment of materials.

30.2 Materials and Methods

30.2.1 Criticality Assessment

We characterize the material criticality by a series of risk metrics: abundance risk, conflict material risk, monopoly of supply risk, sourcing and geopolitical risk, environmental country risk, and price volatility risk. These risk metrics are selected because they are highly linked to the different risk aspects from business perspectives represented by the critical materials. For example, the companies are required by legislation to declare when materials are sourced from the conflict regions, so that the political risk can be quickly and efficiently identified using conflict material risk metric. For another example, the companies may be exposed to price volatility risk due to the use of critical materials of high value. Hence, the decision-makers, especially the risk managers in the commercial organizations, are familiar with the use of risk terms and the data for these metrics are available in numerous databases (for this research we have used data found in the GRANTA MI database) (Granta Ansys 2017). These metrics are represented by numerical indicators, based on which linguistic risk levels are defined.

Table 30.1 Abundance risk level

Abundance in the Earth's crust (ppm)	Abundance risk level
<0.01	Very high
[0.01, 1]	High
[1, 100]	Medium
[100, 10,000]	Low
>10,000	Very low

- **Abundance risk**

Abundance risk is based on the value of abundance in parts per million (ppm) of material in the Earth's crust (Haynes 2014). The values of abundance have been estimated in the literature and a suitable range is provided associated with qualitative risk levels (Table 30.1).

- **Conflict material risk**

The conflict material risk indicates the risk that materials that have been obtained from conflict minerals, whose production or trade are used to finance the regional violence. At this moment, this definition is only applied to the minerals from the Democratic Republic of Congo and its adjoining countries (Yager 2007). A material can be assigned to three risk levels according to the minerals and countries it is produced (Table 30.2).

- **Monopoly of supply risk**

The monopoly of supply risk indicates the level of concentration of production of a raw materials within any country. Generally, the Herfindahl-Hirschman Index (HHI) of a material is calculated using the percentage of the worldwide production (by mass) in each of the country as indicator for the monopoly risk (Wikipedia Contributors 2019). A value close to 0 indicates that the production is widely distributed in many countries, while a value close to 10,000 indicates that the production is highly concentrated in a small number of countries. GRANTA database divided the HHI values into five scales associated with five risk levels (Table 30.3).

Table 30.2 Conflict material level

Risk category	Conflict material risk level
Conflict mineral as defined in US conflict minerals law	High
Other elements minerals reported to be sourced from DRC and adjoining regions	Caution (Low)
Absence of reliable information	None

Table 30.3 Monopoly of supply risk

HHI scale	Monopoly of supply risk level
<2001	Very low
[2001, 4001]	Low
[4001, 6001]	Medium
[6001, 8001]	High
>8001	Very high

Table 30.4 Sourcing and geopolitical risk

HHI_{WGI} scale	Sourcing and geopolitical risk level
>4	Very high
[3, 4]	High
[2, 3]	Medium
[1, 2]	Low
<1	Very low

- **Sourcing and geopolitical risk**

The sourcing and geopolitical risk indicates the supply disruption risk due to political factors (e.g., political stability and control of corruption) in the country in which a raw material is produced, as well as the concentration of worldwide production. Therefore, the sourcing and geopolitical risk indicator is a modified and scaled HHI with the consideration of Worldwide Governance Indicator (WGI) for the producing country (World Bank 2010), denoted as HHI_{WGI}, based on which five qualitative risk levels are assigned (Table 30.4).

- **Environmental country risk**

The environmental country risk indicates the risk that worldwide supply of a material may be restricted in the future as a result of environmental protection measurement in any producing countries. It is calculated based on the HHI and the Environmental Performance Index (EPI) (Yale 2018), denoted as HHI_{EPI}, based on which five qualitative risk levels are assigned (Table 30.5).

- **Price volatility risk**

Price volatility indicates the fluctuation in the historic price of a raw material over the past five years, based on which five price volatility risk levels are assigned (Table 30.6).

GRANTA database already contains some material property information for assessing risks associated with critical materials. Information about different risk metrics provides the decision makers with an overall understanding of critical material risks, not only from an economic perspective, but also from environmental and social aspects. Although some of metrics can be quantified as precise values, it is

Table 30.5 Environmental country risk

HHI_{EPI} scale	Sourcing and geopolitical risk level
>4	Very high
[3, 4]	High
[2, 3]	Medium
[1, 2]	Low
<1	Very low

Table 30.6 Price volatility risk

Price volatility (%)	Risk level
>400	Very high
[300, 400]	High
[200, 300]	Medium
[100, 200]	Low
<100	Very low

difficult to normalize the metrics values in the same scale for trade-off purposes. On the other hand, the decision makers are comfortable with using linguistic terms as qualitative expression given imprecise information. Therefore, we propose a fuzzy linguistic approach to represent the risk levels of the six metrics in order to derive a single criticality indicator.

30.2.2 Fuzzy Linguistic Approach

The fuzzy linguistic approach is based on fuzzy set theory, by which the degree of membership (denoted as $A(x) \in [0, 1]$) indicates the confidence that an element x belongs to a universal set X (Klir and Yuan 1995). In fuzzy set theory, the degree of membership is modelled by membership function (MF). The choice of MF shapes depends on both the users' experiences and problem types. For comparative evaluation in this study, we choose two most commonly-used MFs: triangular and trapezoid MF due to their simplicity and computational efficiency (Pedrycz 1994). For both triangular and trapezoid MFs, the parameters are subjectively defined, which refer to the user's intuitive thinking about the linguistic terms.

The triangular MF is denoted as A (a_L, a_M, a_R), where a_L and a_R are the left (lowest) and right (highest) bounds of the element x, a_M is the mode of the triangular MF (Eq. 30.1).

Equation 30.1: Triangular membership function

$$A(a_L, a_M, a_R) = \begin{Bmatrix} \frac{x-a_L}{a_M-a_L} \text{ for } a_L \le x \le a_M \\ 0 \quad \text{otherwise} \\ \frac{a_R-x}{a_R-a_M} \text{ for } a_M \le x \le a_R \end{Bmatrix} \tag{30.1}$$

in which $0 \le a_L \le a_M \le a_R$

The trapezoid MF is denoted as A (a_L, a_{LM}, a_{RM}, a_R), where a_L and a_R are the left (lowest) and right (highest) bounds of the element *x*, a_{LM} and a_M is the range of the mode of the trapezoid MF (Eq. 30.2).

Equation 30.2: Trapezoid membership function

$$A(a_L, a_{LM}, a_{RM}, a_R) = \begin{Bmatrix} \dfrac{x - a_{LM}}{a_{LM} - a_L} \; for \; a_L \le x a_{LM} \\ 1 \; for \; a_{LM} \le x \le a_{RM} \\ \dfrac{a_R - x}{a_R - a_{RM}} for \; a_{RM} \;\; \le x \; a_R \\ 0 \quad \text{Otherwise} \end{Bmatrix} \tag{30.2}$$

$$in \; which \; 0 \le a_L \le a_{LM} \le a_{RM} \le a_R$$

As mentioned in the previous section, risk metrics have five levels ("*very low*", "*low*", "*medium*", "*high*" and "*very high*"), so we assume that each risk level has symmetric MF and the distance between two adjacent levels is equal. Thus, the triangular MF is assumed to model the risk levels. The MF parameters are assigned for each level within the scales [0, 5] based on the assumption, shown in the following table (Table 30.7). The option "None" is applied when a risk metric is not concerned for a material.

To assess the importance of risk metrics to the overall criticality, the trapezoid MF is assumed to represent importance weight ("*Very small*", "*Small*", "*Fair*", "*Big*" and "*Very big*") of each metric within the scale [0, 1] (Table 30.8).

Table 30.7 Triangular MF parameters for risk levels

Risk level	MF parameters		
	a_L	a_M	a_R
Very low	0	1	2
Low	1	2	3
Medium	2	3	4
High	3	4	5
Very high	4	5	5
None	0	0	0

Table 30.8 Trapezoid MF parameters for importance weight

Importance weight	MF parameters			
	a_L	a_{LM}	a_{RM}	a_R
Very small	0	0	0.1	0.2
Small	0.1	0.2	0.3	0.5
Fair	0.3	0.5	0.5	0.7
Big	0.5	0.7	0.8	0.9
Very big	0.8	0.9	1.0	1.0

30.3 Application of Fuzzy Linguistic Approach

We use the pre-defined MFs to transfer the linguistic terms to fuzzy numbers, in order to assess the criticality of three raw materials: Cobalt, Tungsten and Yttrium, as follows:

Step 1. Define the membership functions for risk metrics and importance weight, shown in Table 30.7 and Table 30.8;

Step 2. Use linguistic terms to assess the risk level of each metric (Table 30.9) and its corresponding importance weight (Table 30.10);

Step 3. Aggregate the MFs of metrics and importance weights by Eq. 30.3;

Equation 30.3: Aggregation of membership functions

Table 30.9 Risk levels of three critical materials

1 Risk metric	Critical material		
	Cobalt	Tungsten	Yttrium
Abundance risk	M (2, 3, 4)	M (2, 3, 4)	M (2, 3, 4)
Conflict material risk	L (1, 2, 3)	H (3, 4, 5)	L (1, 2, 3)
Environmental country risk	L (1, 2, 3)	M (2, 3, 4)	VH (4, 5, 5)
Price volatility risk	VL (0, 1, 2)	VL (0, 1, 2)	M (2, 3, 4)
Sourcing and geopolitical risk	M (2, 3, 4)	H (3, 4, 5)	VH (4, 5, 5)
Monopoly of supply risk	L (1, 2, 3)	H (3, 4, 5)	VH (4, 5, 5)

Table 30.10 Importance weights of six risk metrics

Risk metric	Importance weight
Abundance risk	Small (0.1, 0.2, 0.3, 0.5)
Conflict material risk	Big (0.5, 0.7, 0.8, 0.9)
Environmental country risk	Fair (0.3, 0.5, 0.5, 0.7)
Price volatility risk	Very big (0.8, 0.9, 1.0, 1.0)
Sourcing and geopolitical risk	Fair (0.3, 0.5, 0.5, 0.7)
Monopoly of supply risk	Fair (0.3, 0.5, 0.5, 0.7)

$$X = \begin{bmatrix} x_{L,1}, x_{L,2}, \ldots x_{L,n} \\ x_{M,1}, x_{M,2}, \ldots x_{M,n} \\ x_{R,1}, x_{R,2}, \ldots x_{R,n} \end{bmatrix} * \begin{bmatrix} W_{L,1}, W_{LM,1}, W_{RM,1}, W_{R,1} \\ W_{L,2}, W_{LM,2}, W_{RM,2}, W_{R,2} \\ \ldots \\ W_{L,n}, W_{LM,n}, W_{RM,n}, W_{R,n} \end{bmatrix}$$
$$= \begin{bmatrix} x_{L,1} * W_{L,1} + x_{M,1} * W_{LM,1} + x_{M,1} * W_{RM,1} + x_{R,1} * W_{R,1} \\ x_{L,2} * W_{L,2} + x_{M,2} * W_{LM,2} + x_{M,2} * W_{RM,2} + x_{R,2} * W_{R,2} \\ \ldots \\ x_{L,n} * W_{L,1} + x_{M,n} * W_{LM,n} + x_{M,n} * W_{RM,n} + x_{R,n} * W_{R,n} \end{bmatrix}$$
$$in\ which\ x\ indicatesrisklevel,\ w\ indicates\ importance\ weight,\ and\ n\ is\ the\ number\ of\ riskmetrics. \tag{30.3}$$

Step 4. Construct the aggregated membership function for each material and rank the fuzzy numbers as critical level (Table 30.11 and Fig. 30.1).

Therefore, the ordering of the critical level is:

$C_{Yttrium} > C_{Tungsten} > C_{Cobalt}$

30.4 Discussion

Addressing material criticality for business benefits requires a full understanding of material's supply risk and economic vulnerability through the supply chain. Both

Table 30.11 Aggregated MF parameters for three critical materials

Material	MF parameters			
	a_L	a_{LM}	a_{RM}	a_R
Cobalt	1.9	6.4	7.0	13.7
Tungsten	4.1	9.8	10.6	18.3
Yttrium	5.9	12.2	13.0	19.2

issues are influenced by various factors, such as economic, environmental, geopolitical and sociological risks. The classification of critical or non-critical materials defined by the commonly-used two-matrix or three-dimensions approaches may make the decision makers pay more attention to certain materials at a global level, while our approach provides a more detailed "dashboard" of risk metrics regarding the raw materials used in their particular systems at a regional or business level. Thus, from business perspective, criticality assessment should consider multiple factors given that different systems may be exposed to different risks which in turn trigger different business strategies to mitigate the risks. The risk metrics defined in this paper support the evaluation of supply chain risk of a critical material. The results indicates that Yttrium is the most critical materials among the selected three materials, due to its very high risk levels in the aspects of environmental country risk, sourcing and geopolitical risk, and monopoly of supply risk. This is because the supply of Yttrium is mainly dominated by a few countries, like China (95% of global production and 41% of shares of reserves), as well the mining and processing of Yttrium causes serious environmental problems (Zhang et al. 2017). Based on such results, the decision makers can focus on the strategies to either exploit potential markets outside China (e.g., US, Australia, India) in order to reduce supply risk, or formulate more strict regulations to the material mining and processing operations for environment protection. Therefore, the multiple risk metrics for criticality assessment can support the decision makers to identify and manage the risks of the biggest concern at a business level. However, there are mainly two limitations. The first one is that quantitative data are not always available or are too costly to be collected. The second one is that "trade-off" problem arises when using multiple risk metrics that are measured in different scales, so diverse aggregation approaches may yield different results. Therefore, the fuzzy linguistic approach is proposed to overcome these limitations.

In real-world communication, people are more inclined to use natural language intuitively for qualitative assessment (e.g., quality evaluation, expert elicitation), especially when no quantitative information is available. Even in this case, the quantitative data has been translated to linguistic terms to assess the risk level, because the decision makers usually rely on the risk terms rather than the numerical values.

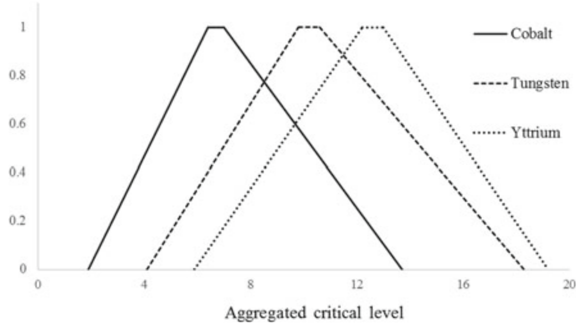

Fig. 30.1 MF structures of the aggregated critical levels for three critical materials

The proposed fuzzy linguistic approach has the advantage to represent directly the linguistic terms and preserve the imprecision within the representation modelled by membership function. Since the risk metrics are modelled under the same scale, the critical levels of all the metrics can be aggregated easily to obtain an overall critical level, which also contains the imprecision. As a result, the critical levels of materials are ranked allowing comparison. The capability of the ranking system enables the decision makers to mitigate the business risks and maximize opportunities for raw material selection.

This study also considers the importance of each metric to the overall criticality level, so the importance weight is subjectively attributed to each risk metric in terms of natural language, then modelled by the membership function. For example, the price volatility risk is considered to be very important, because the price volatility is calculated on the historic price fluctuation that may not predict the future price variation. Hence, there is uncertainty in the price volatility risk that affects the assessment of the overall criticality. The integration of importance weight into risk metrics allows the capture of experts' knowledge regarding the sensitivity of risk metrics. However, the users should be aware that importance weighting is likely to be subjectively different among the experts and it is sometimes difficult to reach a consensus. Therefore, in a real case, the justification of weighting attribution should be well documented or a specific workshop should be organized to create consensus among the experts. For example, the Delphi method is commonly used for qualitative expert elicitation, delivering group consensus (Helmer and Gordon 1968).

30.5 Conclusion

This study applies fuzzy linguistic approach to assess the criticality of raw materials with multiple risk metrics when quantitative data are limited or non-existent. As the material criticality is determined by various factors that usually change over time, so the indicators of risk metrics should also be temporally updated according to the specific business perspectives. More indicators are considered, more data are required. Since detailed quantitative data capture requires significantly more time and economic resources, linguistic information is relatively easy to be captured. This approach models appropriately linguistic information with imprecision, which expresses the experts' knowledge in a user-friendly format - natural language. However, the use of linguistic terms loses the precision comparing with the numerical values. Therefore, the users should be aware whether or not their underlying studies require high level precision. From our perspective, this research could extend to more strategic functions, for example, integrating proactive judgments with the risk metrics may help the decision makers to identify potential future critical materials.

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Chapter 31
Development of a Method for Measuring Resource Efficiency for Product Lifecycle

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Abstract In recent years, increasing the efficient use of material resources by circulating them (through reuse, refurbishment, remanufacturing, and recycling) has become an important global goal. However, quantitative methods of measuring resource efficiency during the product life cycle have not previously been established. In this study, we built a framework for a measurement method with two features. The first feature concerns the change in a product's value due to the reuse, refurbishing, and remanufacturing of products. The second feature is the difference in environmental impact based on the type of material used. As a case study, we formulated five scenarios for refrigerated showcases. In our presentation, we review existing methods for measuring the resource efficiency of products and present our proposed method. Then, we introduce the refrigerated showcase product business of Panasonic Corporation. Next, we describe the baseline and four alternative scenarios developed for our analysis, and we present the results as calculated using different methods. Finally, we discuss the effectiveness of the various measurement methods.

Keywords Resource efficiency · Lifecycle assessment · TMR · EDIP

31.1 Introduction

In recent years, shortages of material resources have been worsening due to population growth and worldwide modernization. Therefore, to end humanity's widespread reliance on a single-use economy that consumes and discards resources, developing a "circular economy" pervaded by reuse and recycling practices has been a subject of considerable investigation, especially in Europe.

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Society's expectations regarding sustainable resource use are growing, especially in countries where the importance of the circular economy is widely acknowledged. Given this trend, even at the G20 Ministerial Meeting on Energy Transitions and Global Environment for Sustainable Growth, held in Japan in 2019 (G20 Ministerial meeting on energy transitions and global environment for sustainable growth (15–16 June 2019), the importance of participation by companies in helping to promote the circular economy was emphasized.

Sustainability is especially important for manufacturers, who use resources intensively in their manufacturing processes.

Panasonic undertakes initiatives such as reusing iron and plastic from end-of-life products in our own products, in accordance with a scheme that we call "Product to Product."

Recycling rates of household appliances are generally used as indicators to evaluate the effectiveness of recycling efforts, but these methods can evaluate only the total amount recycled or the total waste reduced. There is no established index to quantitatively measure resource efficiency, i.e. the extent to which resources are effectively circulated and thus reused.

Therefore, we conducted joint research at Panasonic and AIST with the goal of constructing a resource efficiency indicator. We hoped to create a measure that would capture the following three items:

(i) Differences in environmental impact based on not only the quantity of resources used, but also the type of material used
(ii) The difference between resource circulation in which schemes are already established socially (hereafter referred to "social circulation") and resource circulation managed by companies on their own (hereafter referred to as "intentional circulation")
(iii) Ways to provide value through new services such as product sharing.

31.2 Resource Efficiency Indicator

31.2.1 Investigation

First, we investigated indicators about resource. As a result, similar to general environmental impact assessment, resource impact assessment is represented by inventory data and multiplier of resource impact coefficient as shown Eq. 31.1.

$$\text{Resourve impact assesment} = \text{Iventory data} \times \text{Resource impact coefficient} \tag{31.1}$$

Inventory data is data on the type and amount of resources consumed in each step of the product lifecycle. An example of a database is Inventory Database for Environmental Analysis (IDEA) developed by AIST.

Resource impact coefficient is the resource impact per weight of each resource. This is described in detail in Sect. 2.3.

Also, in resource evaluation, for example, there are Factor X and Material Circularity Indicator (MCT).

However, since there is nothing that can evaluate the three items that we place importance.

31.2.2 Resource Efficiency Indicator

For this paper, the framework for indicators to measure resource efficiency was established as follows.

$$\text{Resource efficiency} = \frac{(\text{Number of years of product use} \times \text{Usage value})}{\text{Resource impact in the product life cycle}} \quad (31.2)$$

This formula expresses the extent of value and the length of the value provision period with respect to the environmental impact of resource use (hereinafter referred to as the “resource impact”).

The usage value in Eq. 31.2 is the value provided to the product user by the function of the product. Although the usage value is a very important factor in measuring the resource efficiency of products, for this paper we assigned it a value of 1 so as to focus on resource impact.

The resource impact in the product life cycle (the denominator in Eq. 31.2) will be explained in detail in the next section.

31.2.3 Resource Impact Evaluation Formula

The resource impact was set as follows.

$$\begin{aligned}\text{Resource impact in the product life cycle } &= \sum_i A_i \times a_i + \sum_j B_j \times b_j \\ &- \sum_k \left(X_k - X'_k\right) \times x'_k \quad (31.3)\end{aligned}$$

Lowercase letters in the equation represent the weights for each material type among the resources that make up the product, and uppercase letters represent coefficients that apply to the environmental impact for each type of material resource. The environmental impact coefficients have already been developed, and a detailed explanation of them is provided below. By performing a multiply-accumulate operation, it is possible to accumulate the resource impact of the product based on that for each of the material types constituting the product.

The first and second terms of Eq. 31.3 represent resource inputs during the product life cycle. A and a in the first term denote inputs of virgin material into the product system, while B and b" in the second term indicate inputs of recycled materials. The sum of these terms represents the resource impact of input resources. The third term of Eq. 31.3 expresses the reduction in environmental impact arising from the reuse of resources due to product recycling after use. Here X is the environmental impact coefficient when the product is made from virgin raw materials and X′ is the environmental impact coefficient when the product is made from recycled materials. X is synonymous with A, while X' is synonymous with B. In other words, when a certain material is generated by recycling instead of from virgin raw materials, the corresponding reduction of raw resource use is expressed by an environmental impact coefficient. This coefficient is derived from the difference between the corresponding coefficients. By multiplying that result by x′, the weight of the recycled material, we obtain the amount of reduced resource impact.

31.2.4 Comparison of Resource Impact Coefficients

Generally, two types of environmental impact coefficients represent resource impact. One is a material footprint representing the environmental impact of land disturbance caused by resource mining, which includes the total material requirement (TMR) and the Ecological Rucksacks concept (Halada 2007). The other is a resource depletion characteristic coefficient that indicates exhaustion or scarcity of resources; it includes environmental design of industrial products (EDIP), 1/R based on recoverable reserves, and abiotic depletion potential based on the ultimate resource amount (Itsubo and Inaba and LIME 2, Japan environmental management association for industry (JEMAI) 2010).

The viewpoints of each coefficient are totally different, and each has its advantages and disadvantages, so it is difficult to select one for this indicator. Although one could calculate all these coefficients and then weight each of them to create an integrated index, for this paper we decided to evaluate resource efficiency using just one of the possible coefficients at a time and compare the results.

31.2.5 Representation of the Purpose of This Paper Using Indicators

Based on the resource efficiency indicator above, the evaluation items 1 through 3 as described in 2.1 can be expressed as follows:

(i) By multiplying the weight of each resource by the environmental impact coefficient, the resource impact for each material type is expressed.

(ii) Expression by calculating and substituting the environmental influence coefficient of the second term of Eq. 31.3 with social or intentional circulation.
(iii) By substituting this coefficient into the usage value and the number of years of product use from Eq. 31.2, the impact of sharing and reuse measures is represented.

To verify the effectiveness of the developed indicator, we conducted a case study with a Panasonic product.

31.3 Case Study

31.3.1 Selection of Environmental Impact Coefficients

In this case study, we used two environmental impact coefficients: TMR, the material footprint, and EDIP, the resource depletion characteristic coefficient.

TMR stands for Total Material Requirement and is the sum of direct and indirect substance inputs and hidden substance flow. It expresses how many kilograms of substances were required to obtain one kilogram of a certain resource. Since using TMR allows the environmental impact to be intuitively understood, it was adopted for this case study.

EDIP is a coefficient weighted for each material type from the perspective of resource depletion. It was adopted because it appears in the item concerning resource depletion in the product environmental footprint methodology being advanced in the EU, where the circular economy framework is flourishing.

31.3.2 Case Study Product

The product for the case study was selected partly due to its involvement with remanufacturing, a topic of lively discussion among circular economy proponents. Manufacturing is a type of product reuse. The manufacturer rebuilds appliances recovered from the market and then ships them back to the market again. Products that are used for a long time and tend to deteriorate with age are suitable for remanufacturing. After some consideration, we decided to use refrigerated showcases installed in supermarkets as our case study product.

Figure 31.1 displays a showcase overview. Food is displayed on each shelf, and refrigeration is required to maintain food freshness. Therefore, a heat exchanger is installed inside the refrigerated showcase.

In addition, steel is often used for the enclosure so that it can withstand the load when food products are displayed. However, when used for a long period of time, the inside of the showcase is humid, so care must be taken to prevent rusting.

Fig. 31.1 Showcase overview

31.3.3 Scenarios

To carry out the case study, we examined five scenarios for the life cycle of refrigerated showcases. We set Scenario 0 as the baseline and created four additional scenarios. Scenarios, were set, and two key driver conditions were also set, so that there were $2 \times 2 = 4$ scenarios (four quadrants).

As shown in Fig. 31.2, each alternative was constructed by choosing between two choices regarding the degree of dependence on used materials and parts and also between two usage period time options, creating $2 \times 2 = 4$ distinct scenarios.

For the "used materials and parts" condition, the two possibilities were use of virgin materials and new parts or of recycled materials and parts. For the "usage period at one store" condition, the two options were "short" or "long."

See Table 31.1 for a description of the four scenarios.

In this case study, the usage value is the same in all scenarios. Specifically, in the supermarket, we decided to provide the function of cooling a certain amount of food. The contents of each scenario concept were set as shown in Table 31.2 while satisfying the usage value.

As a major change, in the scenario where the product is used for a long time, iron is changed to stainless steel for rust prevention.

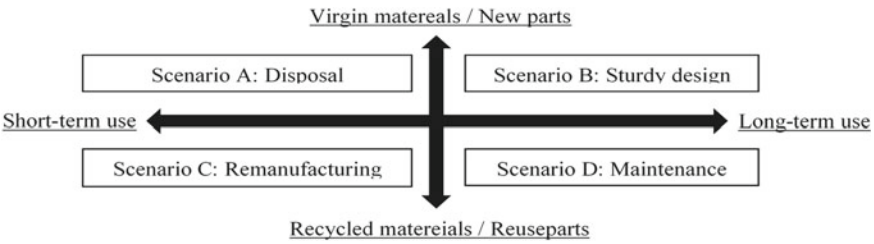

Fig. 31.2 Relationship of each scenario

Table 31.1 Concepts of each scenario

Scenarios	Concept
0: Standard	Use for the typical number of years with the current material composition and dispose of everything in landfills
A: Disposal	Reduce input material by reducing. In exchange, the product life is shortened
B: Sturdy design	Ruggedly designed parts (Enclosure) that are difficult to replace are used, and the product life is extended through daily routine maintenance
C: Remanufacturing	The unit is used for 8 years, leaving only the collected items in the case, regenerating core parts such as heat exchangers (Reman), and used by another user for 7 years as a reman product
D: Maintenance	We replace parts every three years so that we can use the product for a long time, but we replace old parts with reused products

Table 31.2 Contents of each scenario

Scenarios	Usage priod	Material type		Recovery ratio through recycling (%)
		Enclosure	Color panel	
0: Standard	11 years	Steel	Steel(Painted)	0
A: Disposal	4 years	Steel	ABS	70
B: Sturdy design	15 years	Stainless	ABS	70
C: Remanufacturing	8 + 7 years	Steel	ABS	99
D: Maintenance	15 years	Stainless	Stainless (repainted)	70

However, in scenario C, the rust is removed during remanufacturing, so there is no change to stainless steel.

In addition, in this case study the technological evolution of energy-saving effects is not considered so as to simplify the calculations. Therefore, in our comparison of scenarios, the comparison involves only one generation.

31.3.4 Setup Conditions

To calculate the resource efficiency in each scenario, data collection was carried out. Actual product data from Panasonic were used for the materials and weights concerning the refrigerated showcases. For TMR and EDIP, which are the environmental impact coefficients, we referred to the LCA software database (Japan Environmental Management Association for Industry (JEMAI)).

We used recycling test values that Panasonic had obtained for the material type and weight data through recycling. Specifically, we put discarded refrigerated showcases on the line of a recycling plant and utilized the recovery ratio for the material that was actually recovered. In all scenarios, we set the usage value at 1.

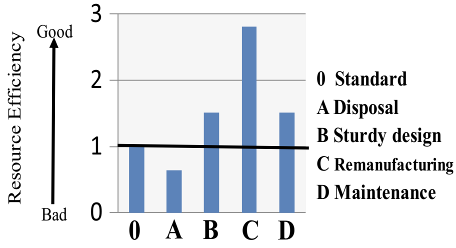

Fig. 31.3 Results of resource efficiency (TMR)

31.3.5 Calculation Results

31.3.5.1 Results and Evaluation Using TMR

For the calculation results, the resource efficiency of Scenario 0 was expressed as 1 and the resource efficiency of each of the four alternative scenarios was expressed as a relative value. The environmental calculation results using TMR are shown in Fig. 31.3. The remanufacturing scenario yielded the best score, whereas the disposal scenario achieved the worst score.

The reason why that Scenario A turned out worse than the others seems to be the extreme shortening of the life span. In other words, if the product has the same material composition as in the baseline scenario, and if the life span can be made longer than X years, the resulting score will be better than in Scenario 0.

On the other hand, Scenario C outperformed the others because the product was designed with remanufacturing in mind. The product could be easily disassembled for recycling after use, and recycling of recovered materials with high purity could be carried out.

In Scenarios B and D, the enclosure material was changed from steel to stainless steel to allow longer-term use. As a result, the resource impact of the input materials increased, but as a result of recovering material with high purity for recycling, the score was better than the baseline Scenario 0.

31.3.5.2 Results and Evaluation Using EDIP

Figure 31.4 shows the results calculated using EDIP. In this calculation, only Scenario C actually scored higher than Scenario 0. The poor score for Scenario A was due to the shortened life span.

In Scenarios B and D, we tried to improve resource efficiency by extending the period of use to 15 years, but it seems that the burden caused by material changes has increased and it has deteriorated.

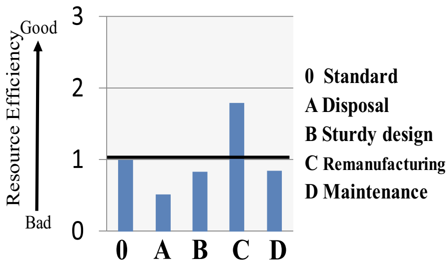

Fig. 31.4 Results of resource efficiency (EDIP)

31.3.5.3 Comparison of Results Using TMR and EDIP

To understand more fully why the scores for Scenarios B and D became extremely low with using EDIP, a graph showing the calculation results as the inversion of Eq. 2 is shown in Fig. 31.5. This graph demonstrates how each choice of materials contributed to the results. We changed the steel used for the enclosure to stainless steel to make the design sturdier and to make maintenance easier.

In Fig. 31.5, the large effect of using sutainless steel, which have high depletion potential, can be seen. Becaouse stainless steel contain highly depleted nickel and cromim. In actual EDIP numbers, the chromium value is about 300 times higher than the iron value, and the nickel value is about 1,300 times higher than the iron value. On the other hand, in actual TMR numbers, the chromium value is about 70 times higher than the iron value, and the nickel value is about 30 times higher than the iron value.

In other words, when one uses the depletion characteristic coefficient in the calculations, material selection at the time of design becomes a dominant factor.

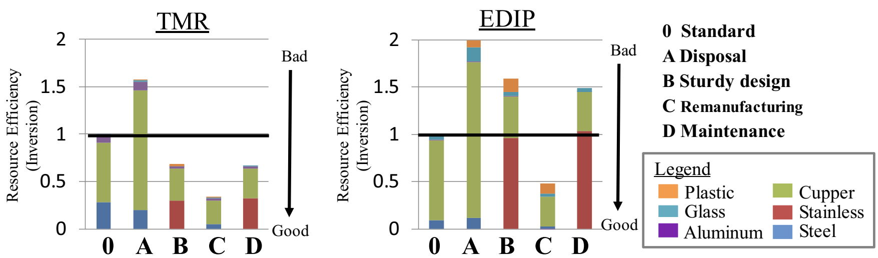

Fig. 31.5 Results of resource efficiency (Inversion, TMR and EDIP)

Table 31.3 Contents of each scenario

Scenarios	Usage period	Consumption of electricity	
		Initial performance	Rate of increase due to aging
0: Standard	11 years	Same	2%/year
A: Disposal	4 years		2%/year
B: Sturdy design	15 years		2%/year
C: Remanufacturing	8 + 7 years		2%/year(Initial performance level is regained due to remanufacturing)
D: Maintenance	15 years		1%/year (Maintenance effect)

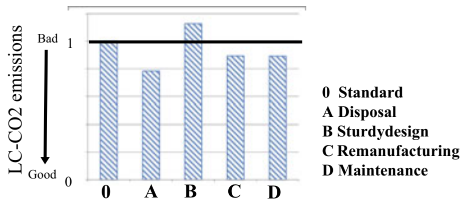

Fig. 31.6 Results of LC-CO2

31.3.5.4 Results and Evaluation Using LC-CO2

In addition to these calculations of resource efficiency, LC-CO2 was also calculated in each scenario. The conditions of the scenario necessary for LC-CO2 calculation were examined. In particular, the consumption of electricity at the time of use, which has an influence on LC calculation, was set as shown in Table 31.3. Figure 31.6 shows the calculation results using LC-CO2. The results indicate that Scenario A's resource efficiency was the worst even though CO2 emissions were the lowest. In Scenario C, both resource efficiency and CO2 emissions are improved over Scenario 0. In the case of TMR, Scenario D improved over Scenario 0 on both measures; in the case of EDIP, Scenario B had better resource efficiency but higher CO2 emissions than Scenario 0.

31.3.6 Discussion

The results differed greatly depending on the selection of the environmental impact coefficient. In every case, however, the length of the usage period greatly affected resource efficiency. Also, the choice of stainless steel to increase the product usage period created a tradeoff in benefits, due to the resulting decrease in resource efficiency.

Although there are differences depending on the type of environmental impact coefficient, the coefficients for nickel and chromium are particularly large, so they tend to affect resource efficiency substantially. In our case study, the effects of nickel and chromium were calculated as larger by EDIP than by TMR. In addition, environmental efficiency was improved by recycling, especially when the material collected had a high level of purity. Although this factor was not examined in our study, there is a danger of double-counting the recycling effect when recycled materials are both used as inputs at the time of manufacturing and then collected for further recycling. Future research should consider this factor when allocating the effects of recycling.

In addition, it seems that the usage value of the product, which was set at 1 for all scenarios in our study for the purpose of simplicity, should greatly affect resource efficiency just as the usage period does, so it will be necessary to develop a method of deriving this value in the future. In addition, although this paper focuses on resource aspects throughout the product life cycle, when designing real products it is necessary to evaluate LC and other costs, and product design and production schemes are also complex and difficult to represent accurately.

31.4 Summary

In this study, we developed indicators to evaluate resource efficiency throughout a product's life cycle. We then conducted a case study on refrigerated showcases, testing four scenarios and examining the quantitative results as determined using TMR and EDIP. As a result, we found that the results differed greatly depending on the choice of the environmental impact coefficient. However, the length of the usage period greatly affected resource efficiency.

In the future, it will be necessary to make comparative evaluations relative to other environmental impact coefficients and to examine the indicators. We also need to conduct case studies with other products and to consider whether this approach can be effectively applied to various types of products.

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Part VI
Energy System Design

Chapter 32
Techno-Economic Analysis of a Hybrid Solar-Hydrogen-Biomass System for Off-Grid Power Supply

Naoto Takatsu and Hooman Farzaneh

Abstract Renewable energy sources are considered as the key solution to tackle the energy-related problems—including global energy supply and environmental challenges facing our society. However, the need for utilizing the renewable energies is increasing, but their dependency on weather conditions makes them unable to provide continuous power supply to the load, because of the uncertainty and intermittent nature. Renewable energy sources, like wind, solar, hydro and biomass can be integrated to form a hybrid system which is more reliable and environmentally friendly. This paper aims at introducing a novel Hybrid Renewable Energy System (HRES) based on the integration of renewable power generation and hydrogen generation from supercritical water gasification of wet biomass feedstock. The Techno-Economic Analysis of the proposed HRES is carried out in order to support the annual electricity demand of a selected household area, in a subject district around the Shinchi station which is located in Shinchi-machi, Fukushima prefecture.

Keywords Hybrid renewable energy system · Simulation · Supercritical water gasification · Fuel cell

32.1 Introduction

Renewable energy sources play a pivotal role to achieve sustainable energy system development. After the Great East Japan Earthquake, Japan has reduced its dependence on nuclear energy, which accounted for more than 30% of Japan's energy mix, drastically below 2% due to the loss of public trust on nuclear power. While Japan is one of the world's leading energy consumers, energy self-sufficiency rate in this country is remarkably low, and its level of dependence on imports of fossil fuels from abroad is high which causes the energy security challenges for Japan.

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Fossil fuels currently account for 83.7% of the total energy consumption in Japan, which approaches the level of the oil shock in 1973 (Agency for Natural Resources and Energy, Japan 2016). To tackle this challenge, the government of Japan needs to develop and utilize renewable energy sources to increase its energy self-sufficiency rate and reduce the environmental impacts of the increased use of fossil fuels.

Since the renewable energies are from the natural environment, they are all weather dependent, which makes them vulnerable in developing a stable power system. The hybridization of variable renewables can allow for smooth, durable, and reliable output to power grids to improve the safety, reliability, and stability of dispatched power, which is cheaper than investing in single renewable technologies. Therefore, Hybrid Renewable Energy System (HRES) can be considered as one possible solution which can combine two or more renewable energy sources to produce power continuously, without interruption. Furthermore, when the HRES is connected to a storage system like battery or hydrogen storage, the excess energy generated by the renewable energies such as solar or wind can be stored and then utilized during the period when there is no sunshine and wind and electricity is not being generated. Therefore, compared to a single renewable technology, the HRES works more efficiently in all operating conditions. There have been reports on HRES using various components so far (Takatsu and Farzaneh, 2020; Shaqour et al., 2020; Yoshida and Farzaneh, 2020; Rodolfo Dufo-Lopez 2008; Guinot 2014; Amer 2013; Sawle 2017).

This paper aims at introducing a novel HRES which consists of a solar panel, a wind turbine, a gasifier system which works based on the Supercritical Water Gasification (SCWG) of biomass feedstocks, a hydrogen tank, a water electrolyzer and a fuel cell which is fed by the Hydrogen to provide power and heat. Figure 32.1 shows the basic configuration of the proposed HRES.

The proposed system was designed to minimize the mismatch between electricity demand and supply in a selected household area in Shinchi-machi of Fukushima-Prefecture, Japan. In this study, the hydrogen is considered to function as an energy storage medium, by storing renewable energies, until the fuel cell converts it to

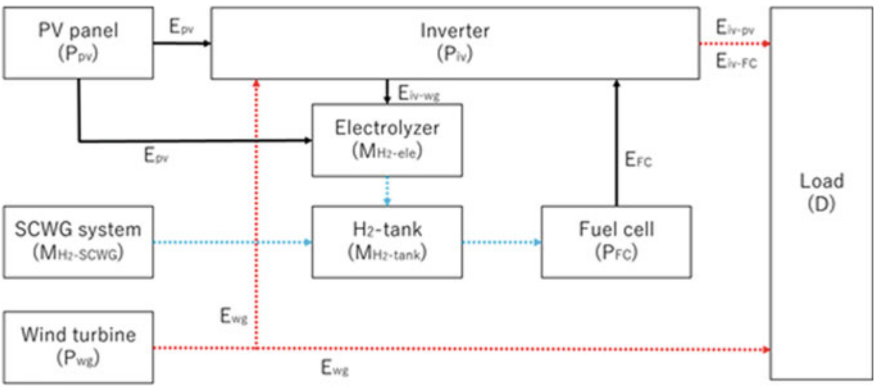

Fig. 32.1 The proposed HRES

electricity. The Hydrogen provided from two sources feed the fuel cell: (1) a water electrolyzer and (2) a SCWG which generates hydrogen from biomass gasification via hydrothermal conversion route (Pichtel 2001). The SCWG uses water as the gasifying agent at its supercritical condition to decompose the organic biomass such as kitchen waste and organic biomass to hydrogen, carbon dioxide, carbon monoxide, and methane gas, allowing to achieve very high volumetric hydrogen ratio.

32.2 Case Study

The case study considered in this paper is a residential area located in a subject district in Shinchi-machi of Fukushima-Prefecture, Japan. This district belongs to the Tohoku region, which the Great East Japan Earthquake occurred there (Shinchi-machi and Official Homepage 2019). A small thermal powerplant provides the electricity load requirements in this district, using imported LNG as fuel. The hourly load curves of the selected household in January and July are shown in Fig. 32.2. As can be observed from this figure, the first ramp takes place between 5:00–8:00 am when people are starting to work in the morning, followed with the second ramp between 4: 00–8: 00 pm when people are getting back to their homes in the evening. Furthermore, electricity consumption is tending to be higher during winter and summer when the air-conditioner usage increases.

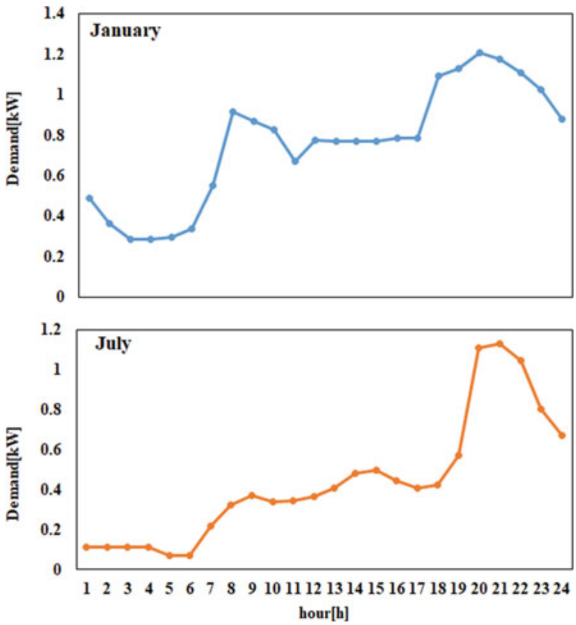

Fig. 32.2 Hourly load profiles in the case study

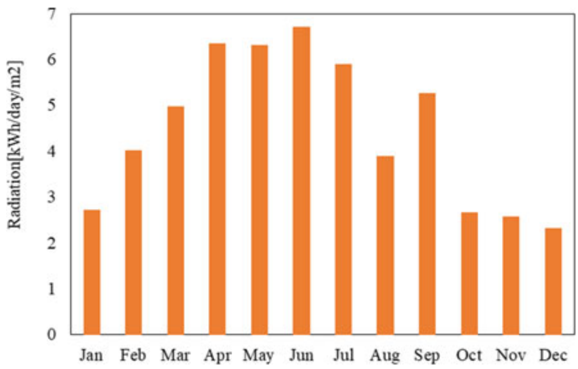

Fig. 32.3 Incident radiation in the selected area

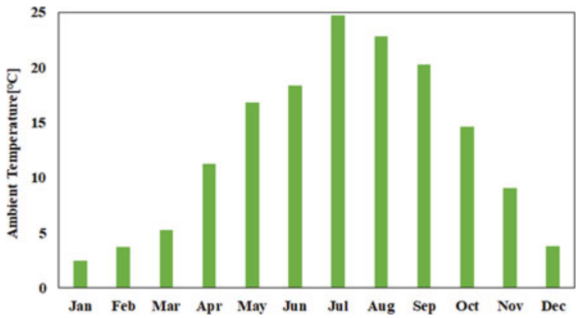

Fig. 32.4 Monthly mean temperature in the selected area

Figures 32.3 and 32.4 illustrate the details of hourly solar irradiation and ambient temperature in the selected area, which were collected from the Japan Metrological Agency.

32.3 Simulation Module

32.3.1 Wind Turbine

The output power from the wind turbine can be expressed, using the following equation: (Hiendro 2013)

$$P_{wg} = \begin{cases} 0, & < V_c \text{ or } V > V_o \\ P_{rate} \frac{V(t) - V_c}{V_o - V_c} & V < V_r \\ P_{rate} & V < V_o \end{cases} \tag{32.1}$$

where, P_{rate}. is the rated power of wind turbine; $V(t)$ is the wind velocity in each time step; V_r is the rated wind velocity and V_c and V_o are the cut-in velocity and cut-out velocity of the wind turbine.

Wind velocity $V(t)$ is dependent to the height of hub of the wind turbine, it can be expressed following Eq. (32.2) (Hiendro 2013):

$$\mathrm{V(t)} = \mathrm{V_{ref}}(t)\left(\frac{\mathrm{H}}{\mathrm{H_{ref}}}\right)^{\alpha} \tag{32.2}$$

where, $\mathrm{V_{ref}}(t)$ is the wind velocity measured at the reference height $\mathrm{H_{ref}}$, and the coefficient α is dependent to roughness of surface, ambient temperature and season. Here, the value of α is assumed to be 0.14 (Hiendro 2013).

32.3.2 PV Module

The PV array power output can be calculated using the following formula (Da-Rosa 2009):

$$\mathrm{P_{out}} = \mathrm{P_{max}F_{PV}}\left(\frac{\overline{\mathrm{I_T}}}{\overline{\mathrm{G_{T,STC}}}}\right)\left[1 + \alpha_p(\mathrm{T_c} - \mathrm{T_{c,STC}})\right] \tag{32.3}$$

$$\mathrm{T_c} = \mathrm{T_a} + \mathrm{G_T}\left(\frac{\mathrm{T_{c,NOCT}} - \mathrm{T_{a,NOCT}}}{\mathrm{G_{T,NOCT}}}\right)\left(1 - \frac{\eta_{cell}}{\tau\,\alpha}\right) \tag{32.4}$$

where, P_{max} is the rated capacity of the PV module under standard test conditions, and F_{PV} is the PV derating factor which is dependent to PV surface condition. $\overline{I_T}$ is the incident radiation to the PV surface, and $\overline{\mathrm{G_{T,STC}}}$ is the incident radiation at standard conditions; which equals to 0.8 kW/m^2 (Da-Rosa 2009). α_p refers to the cell temperature coefficient [%/°C]. T_c is the PV cell temperature in each time step which is calculated by Eq. (32.4). $T_{c,STC}$ is the PV cell temperature under standard conditions (25 °C); $\mathrm{T_a}$ indicates the ambient temperature; $\mathrm{T_{c,NOCT}}$ is the nominal operating cell temperature of the PV module; $\mathrm{T_{a,NOCT}}$ is the ambient temperature at which the NOCT (Nominal Operating Cell Temperature) is defined which value equals to 20°C (Da-Rosa 2009); η_{cell} is cell efficiency which can be assumed to equal to the maximum power point efficiency η_{max}.

The incident radiation to the PV surface is a function of the ambient condition, time, and period of earth revolution which can be calculated by using below equations (Barun K. 2017)

$$\mathrm{I_T} = \mathrm{I_{grobal}}\left\{\left(\cos\theta + \mu\cos\frac{\psi}{2}\right) + \rho\left(\cos\kappa + \mu\sin^2\frac{\psi}{2}\right)\right\} \tag{32.5}$$

where, I_{grobal} is global irradiance on a surface perpendicular to the vector of sunlight; μ is diffuse portion constant for calculation of diffuse radiation as a part of incident radiation; ψ is the tilt angle between the ground which is parallel to horizon and PV panel; ρ is the reflection index that is dependent to ground condition; θ is the angle between the solar rays and κ which is the sun zenith angle; these values are calculated by using the following equations:

$$\cos\theta = \cos\psi\cos\kappa + \sin\psi\sin\kappa\cos(\lambda - \zeta) \tag{32.6}$$

λ and ζ indicate sun azimuth on the celestial sphere and plate azimuth angle. (Radians East > 0 and West < 0)

$$\cos\kappa = \sin\delta\sin\gamma + \cos\delta\cos\gamma\cos\alpha \tag{32.7}$$

$$\tan\lambda = \frac{\sin\alpha}{\sin\gamma\cos\alpha - \cos\gamma\tan\delta} \tag{32.8}$$

$$\delta = -23.45\cos\left(\frac{360}{365} \times (d + 10)\right) \tag{32.9}$$

$$\alpha = 360/24 \times (24T - 12) \tag{32.10}$$

$$T = \text{Local Time} + \text{EOT} - 4L_{local} + 60T_{zone} \tag{32.11}$$

$$\text{EOT} = -9.87\sin 2\beta + 7.53\cos\beta + 1.5\sin\beta \tag{32.12}$$

$$\beta = \frac{360}{364} \times (d - 81) \tag{32.13}$$

where, δ is the solar declination angle on the celestial sphere, which is concerned sun altitude; γ is the latitude in the observed point; α is the solar angle; d is the day number when January 1st in each year is 1; T is the solar time and identified by Eq. (32.12). *Local Time* is local standard time in observed point; EOT is the equation of time to express the relationship earth's revolution speed around sun (minutes); L_{local} is longitude in observed point and T_{zone} is the time difference to GMT (Grennwich Mean Time).

32.3.3 Fuel Cell

The fuel cell which converts the chemical energy of hydrogen and oxygen to electrical energy operates as a backup of the main power components such as the PV panel and Wind turbine. The output power of the fuel cell is proportional to the rate of hydrogen consumption (m_{H_2}) (Kabza 2016):

$$P_{FC} = N \cdot I_{FC} \cdot E_{FC} \tag{32.14}$$

N is the number of cells, and I_{FC} is the current flow of cells. E_{FC} refers to the electromotive energy of fuel cell which is calculated as follows:

$$I_{FC} = \frac{2F\left[\frac{s\,A}{mol}\right]}{N[-] \cdot \upsilon[-] \cdot M\left[\frac{g}{mol}\right]} \dot{m}_{H_2}\left[\frac{g}{s}\right] \tag{32.15}$$

$$E_{FC}[V] = E_0 - b(\log(i) + 3) - R_{ohmic} i - m e^{8i} \tag{32.16}$$

where, F is Faraday constant; υ is the stoichiometry of the reaction; M is the molecular mass of hydrogen; i is the current flow density which is a function of the reaction area (A) as follows:

$$i = I/A \tag{32.17}$$

And b is the Tafel slope:

$$b = \frac{1}{2}\frac{nF}{RT} \tag{32.18}$$

n is the number of exchanged electrons in the reaction; T is the working temperature of fuel cells. Generally, the range of working temperature of PEM (Polymer Electrode Membrane) Fuel cells is between 353.15[K] (80[°C]) to 393.15[K](120[°C]).

In Eq. (32.16), E_0 is the open circuit voltage (OCV). This value is dependent on the working cell temperature:

$$E_0 = -G/nF \tag{32.19}$$

$$G[kJ/mol] = 0.052T[K] - 244.277\left[\frac{J}{mol}\right] \tag{32.20}$$

When working temperature increases, the absolute value of Gibbs free energy decreases. The ohmic loss in Eq. (32.16) can be calculated by using the below equations

$$R_{ohmic} = r_m[\Omega\,cm]L_{mem}[cm] \tag{32.21}$$

where, r_m refers to the specific resistivity for the flow of hydrated protons, and L_{mem} is the thickness of the polymer membrane as given in (Laoun 2016).

32.3.4 Electrolyzer

In a water electrolyzer, water is resolve into hydrogen and oxygen by using electricity. Where, the electricity consumption (ElecEL) of the electrolyzer is identified as a function of rated hydrogen flowrate ($Q_{n\text{-}H2}$) and actual hydrogen flowrate (Q_{H2}) (Sharafi 2013):

$$Elec_{EL} = A_E Q_{n-H_2} + B_E Q_{H_2} \tag{32.22}$$

where, A_E and B_E are the electricity consumption curve coefficients of electrolyzer. The efficiency of electrolyzer is calculated as follows:

$$\eta_{El} = (Q_{H_2} \times HHV_{H_2})/Elec_{EL} \tag{32.23}$$

where, $HHV_{H_2} = 39.4$ [kWh/kg], $A_E = 20$[kWh/kg] and $B_E = 40$ [kWh/kg] from Ref. (Sharafi 2013).

32.3.5 Hydrogen Tank

The amount of hydrogen in the storage tank at time step t is dependent to hydrogen quantity at a previous step (t−1), the hydrogen inflow from the electrolyzer and SCWG at time step t(Q_{H2}), and hydrogen outflow to the fuel cell at the time (t) (Kashefi 2009):

$$H_{2_{level}}(t) = H_{2_{level}}(t-1) + Q_{H_2}(t) - m_{H_2}(t)/\eta_{H_2-tank} \tag{32.24}$$

η_{H_2-tank} is hydrogen tank efficiency when releasing hydrogen to fuel cell. And the hydrogen tank has the minimum (H_{2-min}) and maximum limit (H_{2-max}) of hydrogen level; H_{2-min} can be assumed 5%, and H_{2-max} is 90% of this capacity of hydrogen tank.

32.3.6 SCWG

The K-value model is used to determine the species and their amounts of the following biomass gasification reaction in the equilibrium state at a specific temperature and pressure (Farzaneh, 2019):

$$C_cH_xO_y + wH_2O \rightarrow x_1CO + x_2H_2 + x_3CO_2 + x_4H_2O + x_5CH_4 \tag{32.25}$$

where c, x, and y are given as mole fractions of the biomass feedstock such as glucose. w refers to the mass flow rate of water used in the gasification reaction. The element balances of carbon, hydrogen, and oxygen elements are given below:

$$x_1 + x_3 + x_5 - c = 0 \tag{32.26}$$

$$x + 2w - 2x_2 - 2x_4 - 4x_5 = 0 \tag{32.27}$$

$$y + w - x_1 - 2x_3 - x_4 = 0 \tag{32.28}$$

Since there are just three element equations for five variables, two equations should be more defined. In this study, two thermodynamic equilibrium reactions of water-gas shift and methanation are considered, and their equilibrium constants are defined as the function of their partial pressures [18]:

$$K_1 = \frac{x_{H_2} x_{CO_2}}{x_{H_2O} x_{CO}} \tag{32.29}$$

$$K_2 = \frac{x_{CH_4}}{\left(x_{H_2}\right)^2} \tag{32.30}$$

The values of K_1 and K_2 can be estimated by using the following formulas (Castello 2014):

$$\ln K_1 = \frac{7082.848}{T} + (-6.567)\ln T + \frac{-2.164 \times 10^{-6}}{6} T^2 + \frac{0.701 \times 10^{-5}}{2T^2} + 32.541 \tag{32.31}$$

$$\ln K_2 = \frac{5870.53}{T} + 1.86 - 2.7 \times 10^{-4} T + \frac{58200}{T^2} - 18.007 \tag{32.32}$$

32.4 Results and Discussions

The developed simulation model was used to estimate the amount of electrical power which can be generated by the proposed HRES to satisfy the electrical load requirements in the selected household area.

Table 32.1 Product gas from gasification of 1 kg/h feedstock

Product gas [g/h]			
CO	H_2	CO_2	CH_4
178.7	36.2	383.9	4.2

Using the SCWG model, the amount of product gas from the supercritical water gasification of typical feedstock with a chemical formula of $C_{108}H_{171}O_{63}$ at the operating temperature of 973.15[K] is given in Table 32.1.

The influence of reaction temperature and biomass feedstock moisture content on SCWG product gas are depicted in Figs. 32.5 and 32.6. The carbon monoxide and methane can be used as fuel to set the slurry feed temperature to supercritical state.

Figure 32.7 shows the hourly output power from the solar panel. The extra electricity produced by the solar panel is used to drive the water electrolyzer to produce hydrogen. The hydrogen is stored in a tank and is used later when solar radiation is not available. It can be observed from this figure that the PV output power is higher achieved from April to June in all of the seasons in Shinchi-machi. However, the higher value of the wind turbine output power can be achieved during the spring and winter time (see Fig. 32.8).

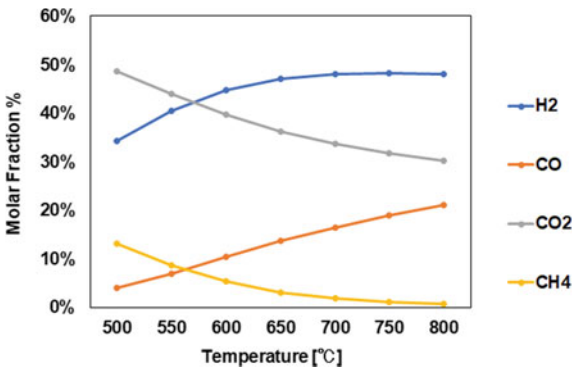

Fig. 32.5 The impact of the operating temperature on SCWG gas production composition

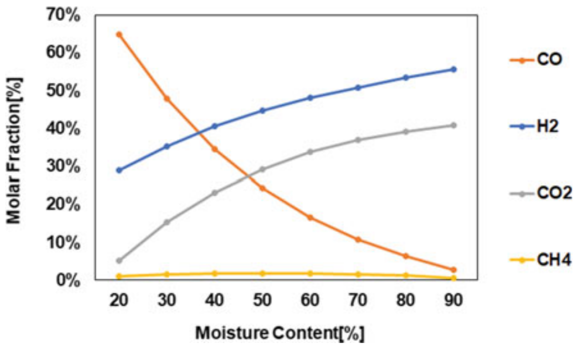

Fig. 32.6 Impact of the feedstock moisture content on SCWG gas production composition

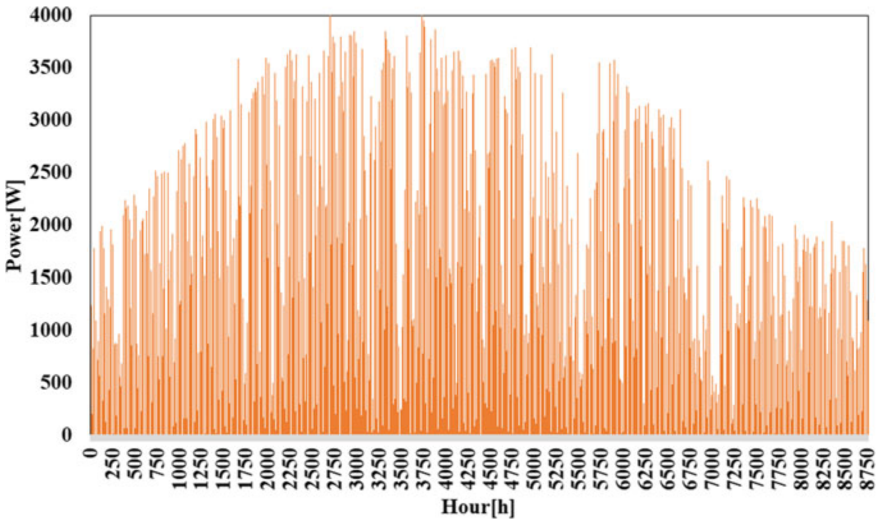

Fig. 32.7 PV panel output power

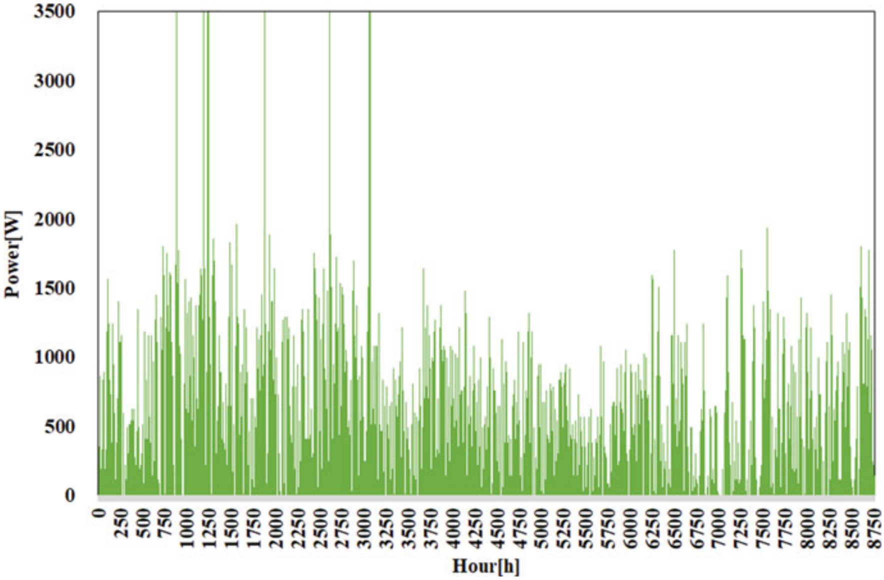

Fig. 32.8 Wind turbine output Power

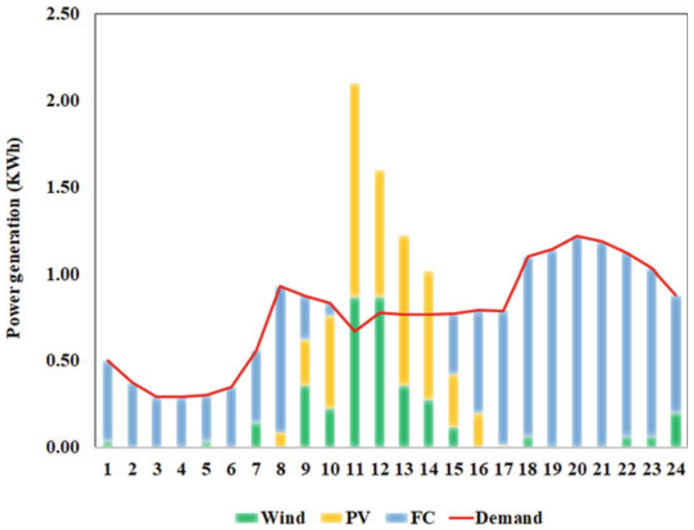

Fig. 32.9 HRES power generation mix in January 1st, 2018 (PV = 4 kW, Wind turbine = 3.5 kW)

Figure 32.9 shows the detailed hourly simulation of the electricity generation by the proposed HRES, using the meteorological data collected on January 1st, 2018.

The total annual electricity generation by the proposed HRES is estimated at 4.73MWh with a total yearly hydrogen production of 63.4 kg. About 58.4 kg of this amount is produced from the water electrolyzer, and the remaining amount should be provided by the SCWG, using the annual waste food consumption of 122.7 kg. The amount of food waste generated from a standard Japanese household with four family members is estimated around 260 kg/y which can sufficiently meet the demand of the biomass feedstock in the proposed HRES [19]. The monthly hydrogen production and electricity generation by the proposed HRES are shown Figs. 32.10 and 32.11.

The economic analysis of the proposed HRES was based on calculating the Levelized Cost of Electricity (LCOE) of the proposed system, using the following formula (Farzaneh, 2019):

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} (I_t + M_t + F_t) + /(1+r)^t}{\sum_{t=1}^{n} (E_t) + /(1+r)^t} \tag{32.33}$$

E_t Electricity generation in year t
r Discount rate
n Lifetime of the system
M_t Operations and maintenance costs in year t
F_t Fuel costs in year t
I_t Investment expenditures in year t.

The cost items of the HRES components is shown in Table 32.2. The operation and maintenance costs of the wind turbine and solar panel are assumed to be about 1.5% and 0.5% of the total investment costs, respectively (NEDO (New Energy

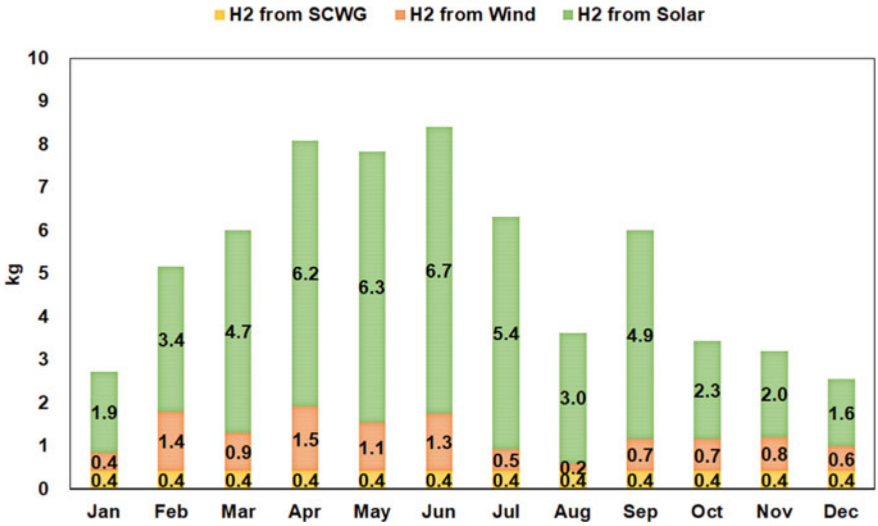

Fig. 32.10 Monthly hydrogen production from the proposed HRES

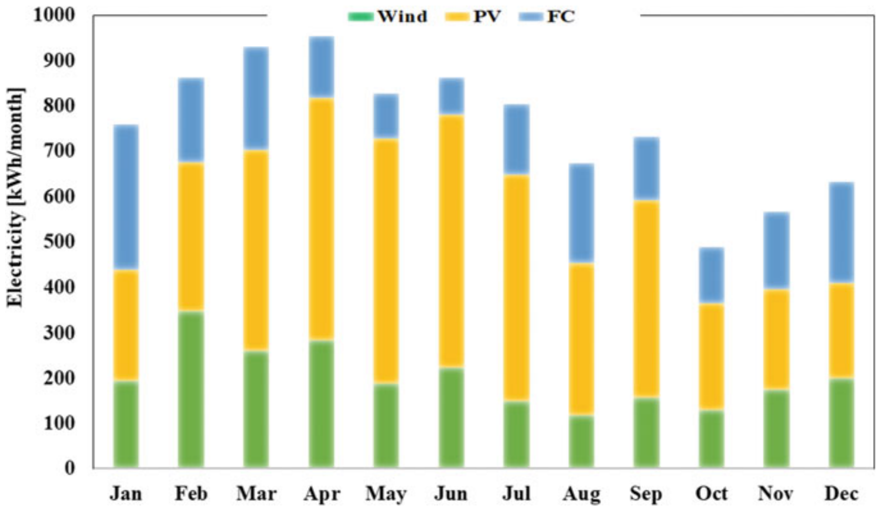

Fig. 32.11 Monthly electricity generation by the proposed HRES

and Industrial Technology Development Organization), Renewable energy white paper (Ver 2.0) 2014). Based on the data reported in Table 32.2, the LCOE of the system was estimated at 51 JPY/kWh. Pao et al. reported the electricity cost is 1.005 USD/kWh in the case of adopting fermentation system as hydrogen production source (Chang 2013); Therefore, the SCWG system is effective as hydrogen source which is relatively inexpensive.

Table 32.2 Cost function of each component

	Unit cost [JPY/unit]	Rated capacity	Investment cost[yen]
PV	2,300,00[1]	4	920,000
Wind turbine	2,700,00[1]	3.5	945,000
H_2 tank	1,500,00[2]	15	2,250,000
Fuel cell	7,000,00[1]	1.5	1,050,000
SCWG	720,00[3]	0.33	23,760

1. JPY/kWh
2. JPY/kg
3. JPY/kg/day

32.5 Conclusion

In this study, to promote the application of the HRES, a novel system based on the integration of water electrolysis and supercritical water gasification of wet biomass feedstock was proposed. The results of the detailed techno-economic analysis revealed that the annual electricity generated by the proposed HRES system could sufficiently meet the load requirements in the selected household area in Shinchi-machi. As indicated by results, the total annual electricity generated by the proposed HRES is about 4.73MWh with a total annual hydrogen generation of 63.4 kg, using the annual wet biomass consumption of 122.7 kg.

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Chapter 33
Optimal Design and Operation of a Residential Hybrid Microgrid System in Kasuga City

Yuichiro Yoshida, Nagashima Keisuke, and Hooman Farzaneh

Abstract This study aims to find the optimal configuration of an autonomous microgrid system which can be used to meet the electricity demand of a small community in the city of Kasuga, Fukuoka Prefecture, Japan. To this aim, an optimization model was developed, using the least cost perceptive approach and the load patterns of the residential end-uses. The proposed microgrid system in this study consists of a cluster of loads and micro sources such as the wind turbines, solar photovoltaic panels, battery storage, and a diesel generator. In this research, the effect of the demand response capabilities and patterns on optimal power generation from the proposed microgrid was investigated by introducing a standard demand pattern for a family, including three residents, living in a standard Japanese house in Kasuga city.

Keywords Renewable energy · Microgrid · Energy storage · Solar · Wind · Diesel · Optimization

33.1 Introduction

After the Great East Japan Earthquake, energy security and vulnerability have become the significant challenges facing the energy system in Japan. Consequently, the rapid increase in power demand was met through higher electricity generation from fossil fuels (coal, oil, natural gas, etc.). It was associated with severe negative environmental impacts in terms of increased greenhouse gas emissions (Phurailatpam et al. 2018). Shifting to Renewable Energy Resources (RERs) can be considered as a vital solution to the problems arisen from the extensive use of fossil fuels in the electric power industry in Japan.

To promote the introduction of RERs on a large scale, following the collapse of public trust in nuclear power due to the Fukushima Daiichi nuclear disaster,

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the government of Japan has introduced several energy resilience programs, particularly in the residential and commercial sectors in urban areas. Among all new concepts in power generation, the residential community Microgrids serve as the self-sustaining and autonomous hybrid power systems which can use a variety of RERs such as solar and wind and operate disconnected from the utility grid when outages occur. However, integrating several energy sources in microgrids also increases the complexity of the system. It is because that the main drawback of RERs is their unpredictable natures, which raises concerns about the reliability of the power to the user (Singh et al. 2016). Besides, the increasing penetration of RERs with intermittent power generation brings more significant technical challenges to maintaining the balance of power supply and demand in the power system. To this aim, diesel generators and battery storages are widely used as backup power to cover the supply and demand mismatch and improve the system stability in microgrids. However, the main disadvantages of using diesel generators with microgrid systems are their costs and environmental impacts from burning fossil fuel such as gas oil, kerosene, or fuel oil (Singh et al. 2016).

The optimal design of a microgrid in autonomous mode needs a solid understanding of the dynamic nature of the distribution network, which challenges the stability and control effectiveness of the system. In addition to the reliability of the system, the economic viability of the system plays a key role in cost-effective design and usage of a microgrid (Yoshida and Farzaneh, 2020; Shaqour et al., 2020).

Based on the above discussion, this paper will address a simulation modeling approach which can be used to estimate the optimal configuration of a proposed microgrid consisting of solar photovoltaics, wind turbines, batteries, and diesel power to meet the power demand of a selected standard Japanese house in Kasuga city in Japan. Figure 33.1 shows the overall configuration of the proposed microgrid in this research.

The optimal design of the proposed microgrid will be carried out based on finding the minimum cost of electricity generation by the system.

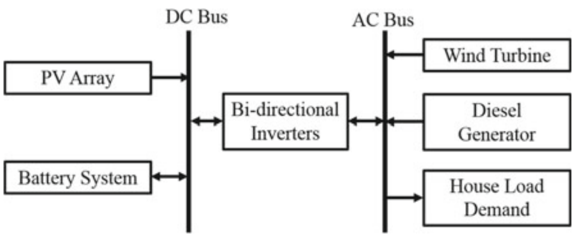

Fig. 33.1 Microgrid system

33.2 Mathematical Modeling of the Proposed System

33.2.1 Wind Power Generation

The amount of power output of a wind turbine is directly proportional to the wind speed, which can be calculated using the following formula (Dhundhara et al. 2018):

$$\mathrm{P_{wt}(V)} = \begin{cases} \frac{\mathrm{P_r(V - V_{CIN})}}{\mathrm{V_{rat} - V_{CIN}}}, & \mathrm{V_{CIN}} \le V \le \mathrm{V_{rat}} \\ \mathrm{P_r}, & \mathrm{V_{rat}} \le V \le \mathrm{V_{CO}} \\ 0, & V \le \mathrm{V_{CIN}}\ and\ V \ge \mathrm{V_{CO}} \end{cases} \tag{33.1}$$

where,

P_r Constant power [kW]
V_{CIN} Cut-in speed [m/s]
V_{rat} Rated wind speed [m/s]
V_{CO} Cutout speed [m/s].

$$\mathrm{V} = \mathrm{V_{ref}}\left(\frac{\mathrm{H}}{\mathrm{H_{ref}}}\right)^{\alpha} \tag{33.2}$$

V referes to the wind speed at the height of H. V_{ref} is the wind speed measured at the reference height, H_{ref}, and α, which is the power-law exponent (Hiendro et al. 2013).

$$\boldsymbol{P_{wt}} = \frac{\boldsymbol{\rho}}{\boldsymbol{\rho_0}} \boldsymbol{P_{wt}(STP)} \tag{33.3}$$

where, $P_{wt}(STP)$ is the wind turbine power output at standard temperature and pressure [kW]. ρ shows the actual air density [kg/m^3]. ρ_0 is defined “the air density at standard temperature and pressure (1.225 kg/m^3). Table 33.1 gives the technical specifications of the Air dolphin pro wind turbine which was used in this study.

Table 33.1 Wind turbine input data (Zephyr AIRDOLPHIN Introduction. http://www.shida-kk.com/images/Airdolphin.pdf)

Constant power [kWh]	2.3
Cut-in wind speed [m/s]	2.5
Cut out wind speed [m/s]	20
Height [m]	30.5
Height of wind speed measurement (high) [m]	80
Height of wind speed measurement (low) [m]	10
Air density on sea surface [kg/m^3]	1.225

33.2.2 PV Power Generation

The amount of power output form the PV array is expressed by the following equation (HOMER 2019):

$$P_{pv} = G_{pv} f_{pv} \left(\frac{I_T}{I_{T,\,STC}} \right) [1 + \alpha_p (T_{C} - T_{C,\,STC})] \qquad (33.4)$$

where,

G_{pv}	Rated capacity of the PV array power, under standard test conditions [kW]
f_{pv}	PV derating factor [%]
I_T	Solar radiation incident on the PV array [kW/m^2]
$I_{T,STC}$	Incident radiation at standard test conditions [kW/m^2]
α_p	Temperature coefficient of power [%/°C]
T_C	PV cell temperature [°C]
$T_{C,STC}$	PV cell temperature under standard test conditions [25 °C].

PV cell temperature is the same as the ambient temperature at night, but it can increase during sunny days. Following equation represents the energy balance of the PV array. The input data used in this study for the simulation of the power out of a selected PV panel (Panasonic HIT 244α) is given in Table 33.2.

$$\tau \alpha G_t = \eta_c G_t + U_L (T_c - T_a) \qquad (33.5)$$

where,

τ Solar transmittance the PV array [%]

Table 33.2 PV Input data (Hiendro et al. 2013) (Panasonic Residential fuel cell. http://panasonic.co.jp/ap/FC/en_index.html.)

Solar constant [kW/m^2]	1.367
Solar radiation at which the NOCT [kW/m^2]	0.8
Ambient temperature at NOCT[a] [°C]	20
NOCT [°C]	44
STC [°C]	25
Rated capacity of the PV array at STC [W/m^2]	194.44
Module efficiency (P_{max}) [%/°C]	−0.258
Slope of the surface [°]	33
Solar absorbance and the solar transmittance [%]	0.194
PV derating factor [%]	0.8
Solar absorbance and the solar transmittance [%]	0.9
Incident radiation at STC [kW/m^2]	1

[a]Nominal Operating Cell Temperature

α Solar absorptance of the PV array [%]
GT Incident solar radiation incident on the PV array [kW/m^2]
η_C Electrical conversion efficiency of the PV array [%]
U_L Overal heat transfer coefficient of the PV [$kW/m^2{}^\circ C$]
T_C PV cell temperature [°C]
T_a Ambient temperature [°C]

33.2.3 Diesel Generation

The fuel consumption of diesel generator is calculated as follows (Jamshidi and Askarzadeh 2019):

$$Cons_G = B_G \cdot P_{N\_G} + A_G \cdot P_G \tag{33.6}$$

where,

$Cons_G$ Fuel consumption of diesel generator [L/h]
P_{N_G} Nominal power of diesel generator [kW]
P_G Power output of diesel generator [kW]
A_G 0.2461 [L/kWh] and BG:0.081451 [L/kWh].

The thermal efficiency of the diesel generator is estimated by using the following equation:

$$\eta_G = \frac{P_G}{Cons_G} \tag{33.7}$$

33.2.4 Battery Modeling

In this investigation, the Kinetic Battery Model was used to determine the amount of energy that can be charged by or discharged from the storage bank in each time step. The Kinetic Battery model explains the behavior of a lead acid battery based on the operation of two storage tank. The first tank contains "available energy", or the amount of chemical energy which is available and can be converted into DC electricity. The second tank represents "bound energy," or energy that is chemically bound and therefore not immediately available for withdrawal. The following equations show the maximum charged by and discharged from the battery bank in each time step (Das et al. 2017):

$$Q_{1,end} = Q_1 e^{-k\Delta t} + \frac{(Qkc - P)(1 - e^{-k\Delta t})}{k} + \frac{Pc(k\Delta t - 1 + e^{-k\Delta t})}{k} \tag{33.8}$$

$$Q_{2,end} = Q_2 e^{-k\Delta t} + Q(1-c)(1-e^{-k\Delta t}) + \frac{P(1-c)(k\Delta t - 1 + e^{-k\Delta t})}{k} \quad (33.9)$$

where,

Q_1	Available energy at the beginning of the time step [kWh]
Q_2	Bound energy at the beginning of the time step [kWh]
Q_{1_end}	Available energy at the end of the time step [kWh]
Q_{2_end}	the bound energy at the end of the time step [kWh]
P	Power into (positive) or out from (negative) the storage bank [kW]
Δt	Time step [h]
k	Constant coefficient which shows how quickly the storage can convert bound energy to available energy or vice versa
c	Battery capacity ratio.

The total amount of energy stored in the battery bank at each time step is the sum of the available energy and bound energy:

$$Q = Q_1 + Q_2 \quad (33.10)$$

The battery state of charge (SOC) is given as follows, whereby Q_{max} is the maximum (rated) capacity of the battery bank:

$$SOC = \frac{Q}{Q_{max}} \times 100(\%) \quad (33.11)$$

The following equation gives the maximum amount of power charged by ($P_{Maxchar}$) and discharged ($P_{Maxdiscahr}$) from the battery bank which can be absorbed over a specific length of time (Δt) (Table 33.3):

$$P_{Maxchar} = \frac{kQ_1 e^{-k\Delta t} + Qkc(1-e^{-k\Delta t})}{1 - e^{-k\Delta t} + c(k\Delta t - 1 + e^{-k\Delta t})} \quad (33.12)$$

$$P_{Maxdischar} = \frac{-kcQ_{max} + kQ_1 e^{-k\Delta t} + Qkc(1-e^{-k\Delta t})}{1 - e^{-k\Delta t} + c(k\Delta t - 1 + e^{-k\Delta t})} \quad (33.13)$$

33.3 Optimization

33.3.1 Cost Analysis

In this study, the Levelized Cost of Energy (LCOE) was considered as a measure for comparative analysis of various power generation technologies (i.e. solar, wind, and

Table 33.3 Battery input data (Dhundhara et al. 2018)

Battery Type	Lead-acid
Nominal cell voltage (V)	12
Nominal cell maximum capacity (Ah)	83.4
Nominal capacity (kWh)	1
Cycle life @ maximum DOD	800
DoD (20–80%)	0.60
Float life	4
Round-trip efficiency (%)	80
Battery rate constant (2.12 h^{-1})	2.12
Battery capacity ratio	0.305
Amount of available charge in the beginning (Ah)	25.43
Storage's maximum charge current (A)	10
Maximum storage bank charge power corresponding to maximum charge current (Ah/Kwh)	0.48
Charging efficiency (%)	85
Discharge efficiency (%)	100
k : Constant coefficient of battery	0.45

diesel) in the proposed microgrid. The LCOE represents the net present value of the total cost of the microgrid over its lifetime, divided by the total output power from the system (DOE Office of Indian Energy Upfront Capital Costs for Renewables.,https://www.energy.gov/sites/prod/files/ 2015):

$$\mathrm{LCOE} = \frac{S_{CL}}{S_{EL}} = \frac{\sum_{i=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{i=1}^{n} \frac{E_t}{(1+r)^t}} \tag{33.14}$$

where,

S_{CL} Sum of costs over the lifetime ($)
S_{EL} Sum of electrical energy produced over the lifetime (kWh)
I_t Investment expenditures in the year t ($)
M_t O&M expenditures in the year t ($)
F_t Fuel expenditures in the year t ($)
E_t Electrical energy generated in the year t (kWh)
r Discount rate (%)
n Expected lifetime of system or power station.

For the battery storage, the following formula may be used to compute the LCOE (What is the true cost to you behind energy storage?,https://www.solarpowerworldonline.com/ 2016):

$$LCOE_{battery} = \frac{P}{C_a \times C_y \times E_f \times DoD} + T_{AC} \tag{33.15}$$

where,

- P Price of the battery storage ($)
- C_y Number of full charge and discharge cycles expected over the guaranteed life of the battery
- C_a Capacity of the battery storage (kWh)
- E_f Storage efficiency (%)
- DoD Depth of discharge (%)
- T_{AC} Total ancillary costs ($).

The cost items, including the capital investment, and operation costs of the main components of the proposed microgrid is given in Table 33.4. Based on these values, the LCOE for each component is derived and is shown in Table 33.5.

Table 33.4 Cost items of each component

Cost Item	Battery (Das et al. 2017)	Wind (Zephyr AIRDOLPHIN Introduction. http://www.shida-kk.com/images/Airdolphin.pdf)	PV (Panasonic Residential fuel cell. http://panasonic.co.jp/ap/FC/en_index.html.)	Diesel (Jamshidi and Askarzadeh 2019)
Capital cost(JPY/KW)	13,600	300,000	730,000	60,000
O&M Cost[1] (JPY/kWh)	1100	1500	3600	130
Life time (years)	4	20	20	3

1. Including the fuel cost

Table 33.5 LCOE for each component

	PV	Wind	Batterty	Diesel
Rated output [kWh/unit]	0.24 (Panasonic Residential fuel cell. http://panasonic.co.jp/ap/FC/en_index.html.)	2.3 (Zephyr AIRDOLPHIN Introduction. http://www.shida-kk.com/images/Airdolphin.pdf)	1	1.9
LCOE [yen/kWh]	40.0	22.4	91.1	151.2

33.3.2 Optimization Model

The objective function of the optimization model is defined as the total cost of electricity supplied by the proposed system as follows (Farzaneh, 2019):

$$Total\,energy\,cost = \sum_{t}\sum_{e} Cost_{e,t} \tag{33.16}$$

where,

$Cost_{e,t}$: the cost of using of each component e $\in [PV, Wind, Battery, Diesel]$ at each hour t ($0 \leq t \leq 23$).

In the above equation, the cost of electricity generated by each component is calculated as follows:

$$Cost_{e,t} = LCOE_e.E_{e,t} \tag{33.17}$$

where,

$LCOE_e$ LCOE of component e,
$E_{e,t}$ Amount of electricity generated by component e in time step t

The cost function is minimized subject to the following constraints:

$$E_{PV,t} + E_{Wind,t} + E_{Battery\_discharge,t} + E_{Diesel,t} \geq E_{Demand,t} \tag{33.18}$$

$$E_{Battey\_Charge,t} = E_{PV,t} + E_{Wind,t} - E_{Demand,t} \tag{33.19}$$

$$E_{Battery,charge,t} \leq P_{Maxchar}.\Delta t \tag{33.20}$$

$$E_{Battery,discharge,t} \leq P_{Maxdischar}.\Delta t \tag{33.21}$$

$$0.2 \leq SOC \leq 0.8 \tag{33.22}$$

$$E_{Diesel,\mathrm{t}} \leq C_{load} P_{Diesel} \tag{33.23}$$

where,

C_{load} The load factor for emergency diesel usage, which is set to 0.7.
$E_{Demand,t}$ Amount of electricty demand at hour t

33.4 Results and Discussions

In this research, a standard demand pattern, so-called “Normal schedule” was considered as the baseline load for a Japanese family, including three residents (Father, Mother, and a kid), living in an average size house (94.13 m^2, 4 rooms) located in Kasuga city, Fukuoka prefecture. The usage method of the main electrical appliances in the normal schedule is shown in Table 33.6. The rated electrical power of each appliance is given in Table 33.7. Accordingly, the load curve in the Normal schedule based on a daily average electricity demand in the selected case study is illustrated in Fig. 33.2. The total amount of electricity demand calculated here was roughly in agreement with the average Japanese household electricity demand based

Table 33.6 Usage schedule

Normal schedule				
Hour	AC	Refregirator	TV	Light
0:00	OFF	ON	OFF	OFF
1:00	OFF	ON	OFF	OFF
2:00	OFF	ON	OFF	OFF
3:00	OFF	ON	OFF	OFF
4:00	OFF	ON	OFF	OFF
5:00	OFF	ON	OFF	OFF
6:00	OFF	ON	OFF	OFF
7:00	OFF	ON	ON	OFF
8:00	ON	ON	ON	ON
9:00	ON	ON	OFF	ON
10:00	ON	ON	OFF	ON
11:00	ON	ON	OFF	ON
12:00	ON	ON	OFF	ON
13:00	ON	ON	OFF	OFF
14:00	OFF	ON	OFF	OFF
15:00	OFF	ON	OFF	OFF
16:00	OFF	ON	OFF	ON
17:00	ON	ON	ON	ON
18:00	ON	ON	ON	ON
19:00	ON	ON	ON	ON
20:00	ON	ON	ON	ON
21:00	ON	ON	ON	ON
22:00	ON	ON	ON	ON
23:00	OFF	ON	ON	ON

Table 33.7 Electric appliances rated power

Electric appliances	Power consumption [kW]	
TV	0.057	
Refrigerator	0.228	
Lighting	0.0358	
Air conditioner (AC)	0.815 (Cooling)	0.957 (Heating)

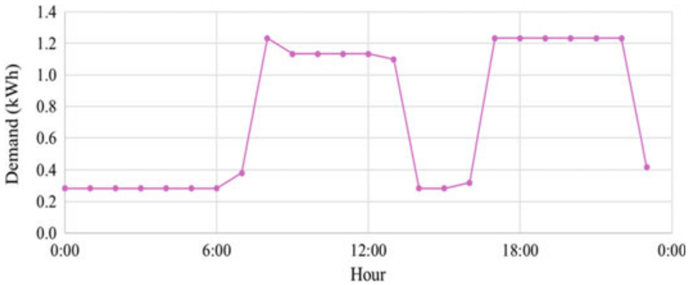

Fig. 33.2 Hourly average demand load curve

on collected data from the agency for Natural Resources and Energy in Japan [Annual Report on Energy (White Paper 2013)].

The developed model was used to estimate the optimum size and capacity of the proposed microgrid system. The optimum configuration of the microgrid comprises a system with a 2.3 kW of the wind turbine, 4.3 kW of the PV panels, six units of 1kWh batteries and 0.5 kW of diesel generator. Based on the results of the optimization model, the hourly electricity supplied by the proposed microgrid in summer and winter is depicted in Fig. 33.3.

Figure 33.4 shows the monthly average electricity supplied by the proposed microgrid. The diesel generator is only used in summer due to lack of availability of wind energy.

Figure 33.5 shows that the battery bank accounts for 50 and 64% of the total cost of electricity generation in summer and winter, respectively.

The modeled LCOE is compared to the existing tariff structure in Japan in Fig. 33.6. The estimated LCOE's of the proposed microgrid is on the order of 64.7 JPY/kWh in summer and 51.26 JPY/kWh in winter which is still well above the average electricity tariff in Japan, creating a cost gap that should be addressed through effective policy and incentive programs in the near future.

33.5 Conclusion

In this paper, modeling and simulation of a fully autonomous microgrid system were conducted in order to find the optimal configuration of the system based on the minimum total cost of the electricity generation. The representative micro-grid

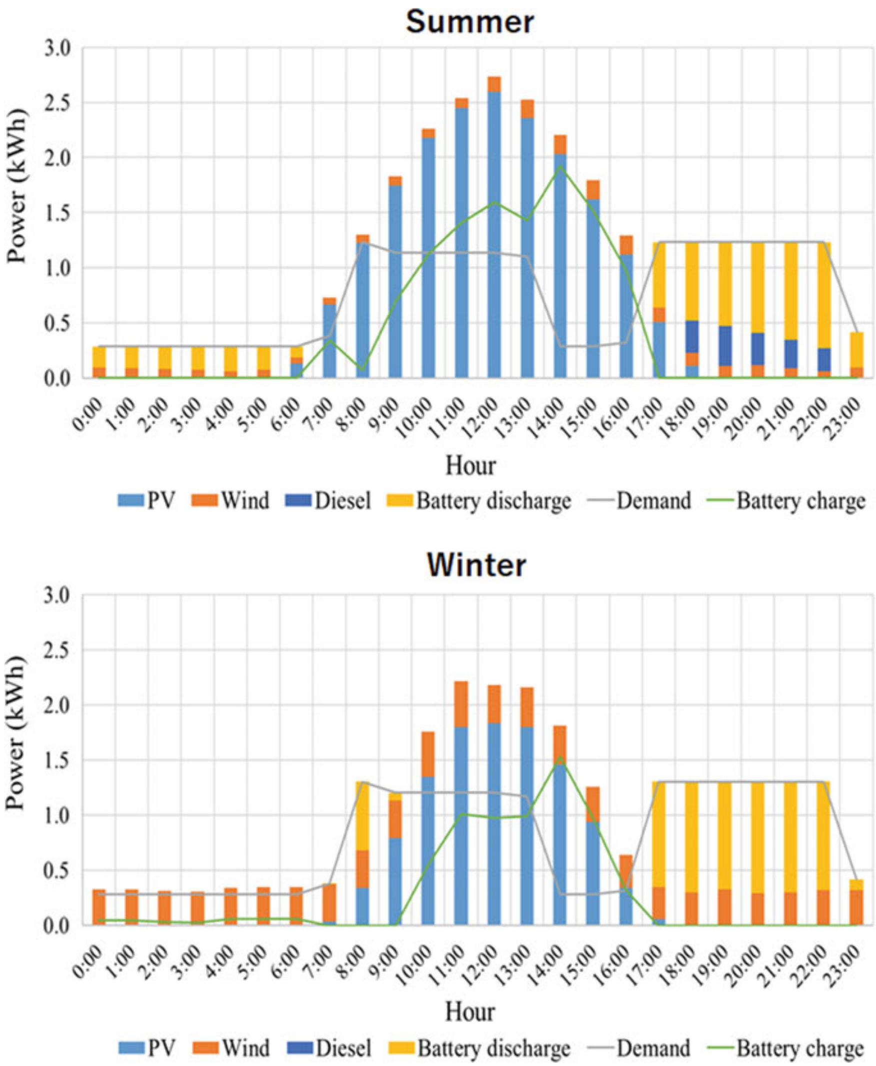

Fig. 33.3 Hourly electricity generation from the proposed microgrid

system considered includes a hybrid solar-wind-battery-diesel generation system, which currently is the most widely applicable and rapidly growing microgrid system type. The proposed microgrid was planned to be analyzed in a standard Japanese house in Kasuga city in Fukuoka prefecture. The results revealed the total power output from the system could sufficiently meet the demand load requirements of the selected household area. This simple analysis offered an estimate of the gap between current tariff regime in Japan and the LCOE of the system which can provide

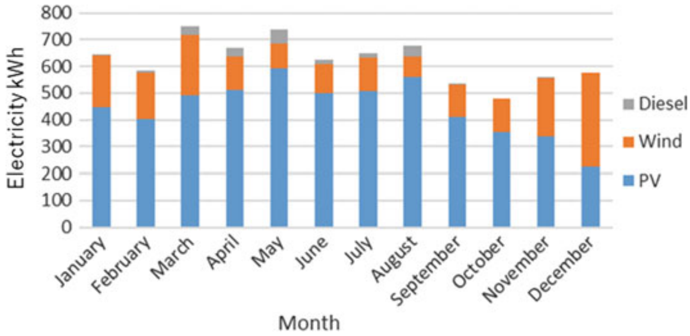

Fig. 33.4 Monthly electricity generation

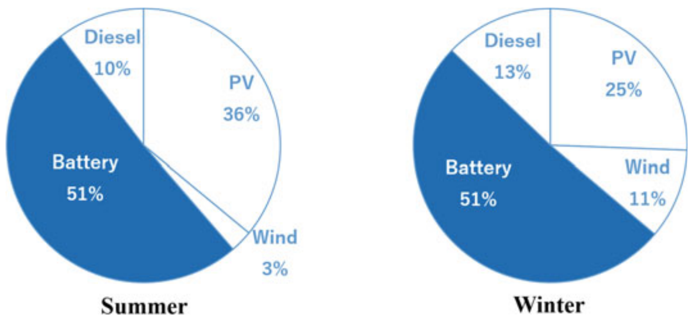

Fig. 33.5 Share of the different components in total electricity generation cost

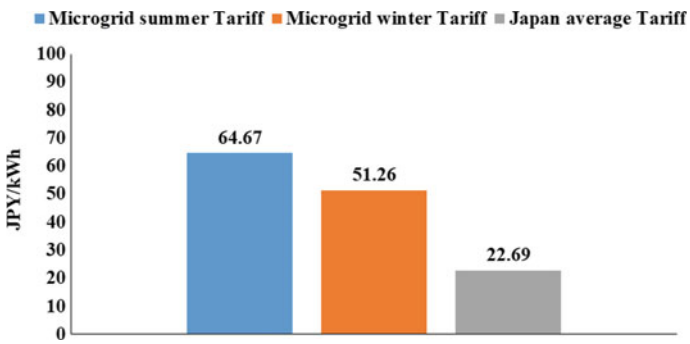

Fig. 33.6 The LCOE comparison

insight into the potential scale of incentives that may be required to enable micro-grid development under the current regulatory structure.

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Chapter 34
Social Equity and Lifestyle Conscious Policy Making for the Energy Transition

Andrew John Chapman and Yosuke Shigetomi

Abstract This research aims to develop a social equity conscious policy making framework, cognizant of lifestyle, consumption, demographics, proactiveness and the distribution of costs and benefits across society. The proposed framework is applicable in multiple jurisdictions, wherever consumption, environmental footprint intensity, and basic societal demographic data are available. For preference weighting, a survey is undertaken to identify stakeholder preferences toward environmental issues and proactive behavior to reduce environmental burdens. A framework is developed and applied to the case study nation of Japan, which is undergoing shifting demographics including both an aging, shrinking population. This novel study demonstrates the nature of societal outcomes through the lens of inequity underpinned by lifestyle related environmental burdens (objective factors) and stakeholder preferences (subjective factors). We identify that the mitigation of environmental footprints leads to improved social equity outcomes, and that stakeholder proactiveness can positively influence both equity and consumption burden outcomes. A key finding is that broad participation is shown to be more effective than targeted participation. Research findings can assist policy makers through an identification of consumption, demographic and footprint trends and their impacts on social inequity and consumption burden outcomes.

Keywords Environmental footprint · Household consumption · Social equity · Transition · Energy policy

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34.1 Introduction

Inequitable distribution of the benefits and burdens of economic activity leads to environmental inequalities. This issue is a growing concern, linked to several factors including but not limited to disparate economic means, participation opportunities, and geographic factors (Boyce et al. 2016). In order to measure these inequalities, the methodology of consumption-based accounting is a recognized approach to quantify upstream environmental burdens of household consumption (Wiedmann 2009). Using household consumption as a proxy for our lifestyles, we can measure both the direct loads (i.e. gasoline combustion for private vehicles) and indirect loads (i.e. food production induced land use changes) utilizing domestic and international supply chains.

The impact of household consumption of lifestyle induced environmental burdens has been researched extensively in the past (Shigetomi et al. 2017; Hertwich 2011), and it has been shown that household footprint variance is not always proportional to household income (Gill and Moeller 2018). At the same time, it has been uncovered that the disparity between household footprints rapidly increases in line with income increases, suggesting this as a reason for the emergence of environmental inequality (Hubacek et al. 2017). Supporting this assertion, it was found that some 34% of global emissions were induced by just 10% of the population, represented by affluent households (Hubacek et al. 2017).

In order to reduce the inequalities emerging between households, recognition of environmental issues and the enacting of countermeasures is essential for householders. To date, precedential literature has largely overlooked these important socio-environmental issues. Studies have identified that stakeholders have varying priorities for both lifestyle and the environment, for example, some may choose to prioritize climate change mitigation, while others may feel that air quality is most important. Age also plays a role, with younger generations identifying income increase as more important than addressing environmental issues, while older stakeholders may have the opposite view due to their individual savings or social welfare status (Chapman and Shigetomi 2018). This societal variations in preference toward environmental, social and economic issues is due to a number of social complexities and is expected to impact upon stakeholders preferred abatement measures at the national and individual level. It is necessary to develop a holistic approach to identify emerging social inequities (i.e. the disparity between generation and allocation of public bads) considering objective and subjective criteria, cognizant of both disparities in environmental burden allocation and the preferences and priorities of stakeholders.

This research seeks to bridge this gap by defining social equity outcomes due to household consumption considering environmental footprints and stakeholder preferences and priorities toward individual footprint related environmental loads. Building on the precedential Energy Policy Sustainability Evaluation Framework (EPSEF) and its application to the visualization of the shape of society and social inequities (Chapman and Shigetomi 2018). Building on past trends of negative environmental impacts (referred to as public bads) including carbon, water, waste, air pollutants and resource mining risk footprints, the emerging social equity gap due to household consumption is estimated. In addition, householder preferences underpinning factor weighting are assessed through a national survey in Japan and applied to the both the quantification of the social equity gap, and the potential for its future amelioration.

34.2 Methodology

The method employed in this research consists of two steps. First, using Japanese household consumption data from 1990 to 2005, environmental footprints are estimated and then projected from 2010 to 2040 using 2005 consumption patterns applied to future demographic trends and stakeholder proactiveness preferences. Second, the extent of social inequity is quantified using a combination of estimated and projected or 'virtual' household footprints. Step one relies on environmentally extended input-output analysis (EEIOA; (Huppes 2006)) while step two utilizes an adapted EPSEF (Chapman and Shigetomi 2018). The combination of these two precedential evaluation approaches is referred to as the Input-Output Sustainability Evaluation Framework (IOSEF) which demonstrates both the basis of social inequity (e.g. the origin of household consumption induced environmental burdens) and the identification of how each household footprint creates inequities within society. Stakeholder preferences (identified through a national survey) are used as a proxy for future stakeholder behavior to aid in the reduction of environmental footprints. These preferences are applied to the 'virtual' footprints, demonstrating stakeholder priority impacts.

This approach is the first attempt at demonstrating societal outcomes through the lens of inequity, underpinned by lifestyle related public bads.

Figure 34.1 describes the approach to quantifying lifestyle-based consumption burden and social inequity levels.

Public bad (PB) values are calculated using Eq. 34.1.

$$PB_j^{(t)} = \sum \frac{Q_{jk}^{(t)}}{Max\,Q_k} \times p_{jk}^{(t)} \tag{34.1}$$

where t is the time period, j is the household attribute for both the quantity (Q) of each footprint, k and stakeholder preferences, p.

The polygon consists of seven rectangles based on the share of total consumption and the normalization of multiple public bads scores by income bracket. In Fig. 34.1, the upper-middle income level is highlighted as an example.

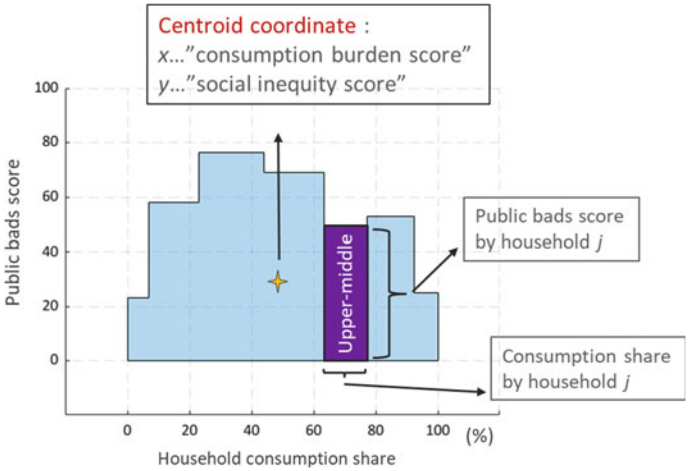

Fig. 34.1 Schematic figure of quantification methodology

34.3 Results

34.3.1 Household Footprint Estimates and Projection of 'Virtual' Footprints

Figure 34.2 details both the estimation of household environmental footprints from 1990 to 2005 based on the Japanese Input-Output Table (TJIO) and those projected between 2010 and 2040.

From 2010 onwards, consumption is projected cognizant of changing household numbers in each income group, using a constant consumption structure as at 2005 (i.e. household consumption and footprint intensities are constant, per-household at 2005 levels). Notably after 2010, the aging, shrinking society anticipated for Japan begins to influence outcomes. Of note is the increase in the mining risk footprint from 1990 to 2005 in response to an increased demand for personal communication devices such as mobile phones and personal computers. All footprints except for water (which peaks in 1995) are expected to peak around 2020.

Incorporating stakeholder preferences from the national survey, post 2020, virtual household footprints are calculated, and compared to a base case which does not consider stakeholder 'proactiveness' in the future. Table 34.1 describes the expected changes in footprint size for each household income level for the year 2040.

By the year 2040, it is anticipated that householder preferences toward environmental improvement will underpin positive behavior leading to a reduction in environmental footprints by up to 9.7% (when compared to non-weighted, base case footprints). The largest change in terms of footprint percentage was seen in blue and green water, with consistently high participation from all income levels. $PM_{2.5}$

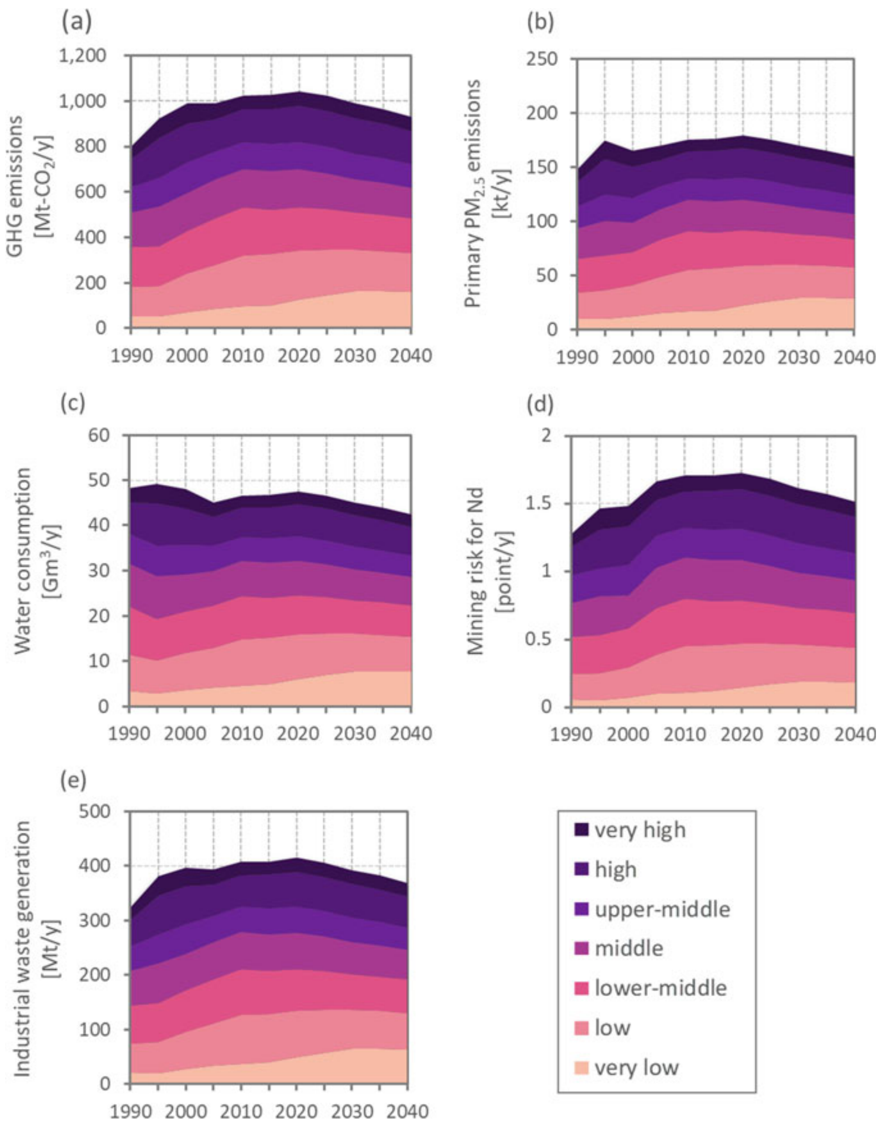

Fig. 34.2 Projected virtual household footprints from 1990 to 2040 for **a** carbon, **b** $PM_{2.5}$, **c** water, **d** neodymium mining risk and **e** industrial waste

and GHG are also expected to be reduced due to proactive environmental behaviors, however no preference toward reducing neodymium mining risk was reported by stakeholders. Interestingly, in terms of GHG reduction, proactive tendencies are only expressed by low, lower middle and very high-income level stakeholders. As the number of low-income households significantly exceeds that of very high-income

Table 34.1 Anticipated household footprint changes due to householder proactiveness in 2040

	GHG [Mt-CO_2eq/y]	$PM_{2.5}$[Mt/y]	Blue & green water [Gm^3/y]	Nd mining risk [point/y]	Industrial waste [kt/y]
Very low	0	−1.45	−0.77	0	−6.31
Low	−8.50	−2.90	−0.78	0	−6.73
Lower-middle	−7.63	−1.29	−0.69	0	−6.09
Middle	0	−1.15	−0.61	0	−5.42
Upper-middle	0	−0.89	−0.47	0	−2.08
High	0	−1.24	−0.64	0	−5.57
Very high	−3.07	−1.09	−0.14	0	−2.44
Expected change	−19.2	−10.0	−4.11	0	−34.8

households, the amount of GHG reduced by their proactiveness is almost triple that of high-income householders. Low income households self-report a high level of proactiveness in our survey, and therefore have the highest overall impact on reducing environmental footprints in all cases.

34.3.2 Social Inequity Impacts Considering Stakeholder Environmental Burden Preferences

In addition to the estimation and projection of virtual household footprints and probable future behavior, consumption burden and relative social inequity scores are determined as detailed in Fig. 34.3. The consumption burden score detailed in panel a represents the origin of public bads in terms of consumption and income level relative to average consumption (i.e. 50% of total household consumption share). In this graph, an increasing score indicates that the majority of public bads are created by households in higher income brackets. A peak is observed in 1995, with a subsequent decline to 2010, moderate increases to 2025 and then a reduction to 2040. This trend can be somewhat explained by the contribution of lower income households to overall environmental footprints through their collective consumption. Considering national income statistics, we observe that the national average income in Japan increased between 1994 and 1998, however after 1999 reduced until 2010. Between 2010 and 2015 a slight increase is observed (MHLW and Ministry of Health Labour and Welfare 2016). As to the future, without direct policy intervention, the aging shrinking society will likely mean that average incomes will decrease out to 2040 (Inagaki 2013).

These public bads which arise from household consumption influence both consumption burden, described in panel a, and social inequity scores as detailed in panel b.

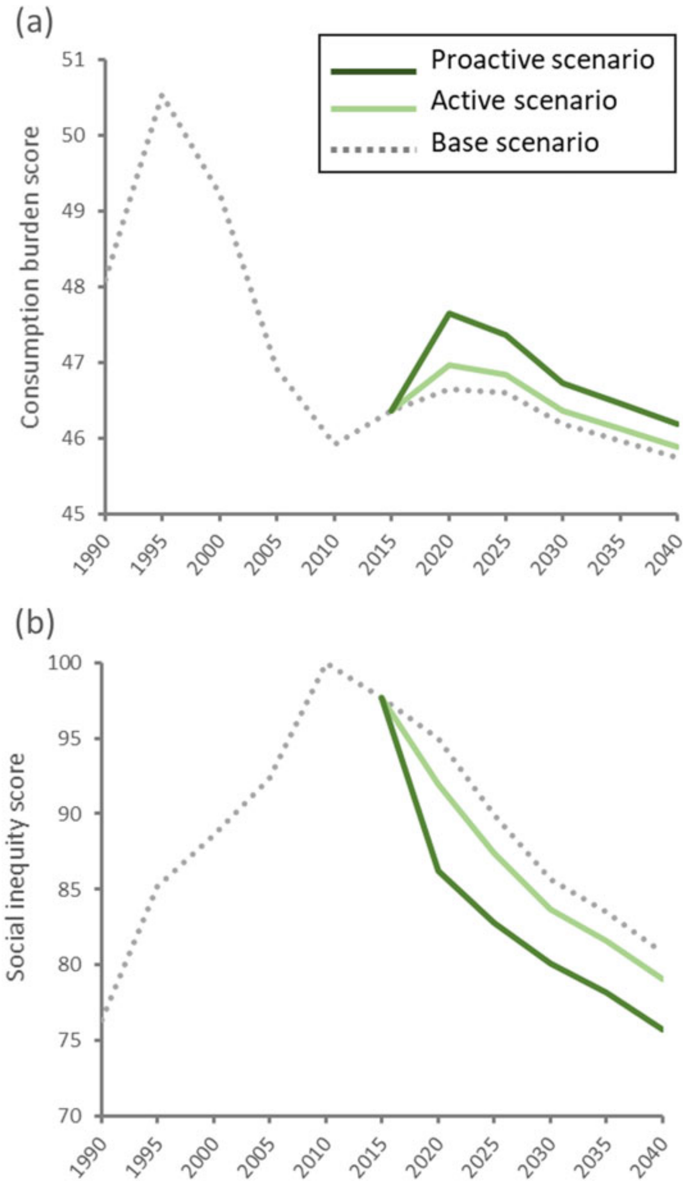

Fig. 34.3 Consumption burden (**a**) and social inequity scores (**b**) for the base case, active and proactive scenarios

Focusing on panel b, a high social inequity score indicates a large, increasing gap between high and low-income households. Although the majority of household footprints peak in 2020, social inequity peaks in 2010. This outcome reflects that the social inequity score is cognizant of both the level of public bads (environmental burdens) and the balance of consumption between households. Post-2010, social inequity scores are expected to reduce.

In addition to the base case, Fig. 34.3 includes two scenarios which reflect stakeholder participation in environmentally conscious activities to reduce their footprints. These scenarios are called the 'active' and 'proactive' scenarios respectively. The active scenario implies a 2.2% change in activity, while the proactive scenarios implies 6.3%. Only under a proactive scenario with broad stakeholder participation in positive environmental behaviors can the level of social inequity be returned to 1995 levels by 2040.

34.4 Discussion

The evaluation methodology proposed in this research, the IOSEF is a useful tool which can aid policy makers through the multi-dimensional measurement of both consumption burden and social inequity across demographic cohorts. In addition, based on the results gained from the Japanese case study, strong evidence can be gathered with regard to stakeholder behavior and appropriate policy development to achieve policy goals. Chief among future policy goals is the reduction of environmental footprints which leads to a reduction in public bads and commensurate amelioration of social inequity. At the national level, the IOSEF is useful in highlighting emerging and priority sustainable development goals (SDGs) which require redress, and also provide an evidence base for their achievement.

The dual indicators of consumption burden and social inequity provide insights which are essential to addressing the social inequity which arises from our lifestyles. Based on the proposed IOSEF, the reduction of each environmental footprint can reduce the social inequity score, leading to an improvement in social equity outcomes. Further, engaging with stakeholders to understand and apply their preferences to future scenarios identifies levels of current consciousness toward desirable futures, and also helps to stimulate proactive behaviors towards improving future outcomes.

One major finding in this research is that broad stakeholder participation (i.e. participation across all income levels) toward reducing environmental footprints has a greater impact than concentrated efforts by fewer stakeholder cohorts. This finding is far reaching in that it identifies the need for inclusive policies which will engender broad participation, rather than policies which target single groups for specific footprint reducing actions.

The approach proposed involves conducting a national survey to identify stakeholder preferences and consumption trends, combined with input-output analysis to determine past environmental footprints and the underpinnings for social inequity and consumption burden impacts. This holistic approach allows for the projection

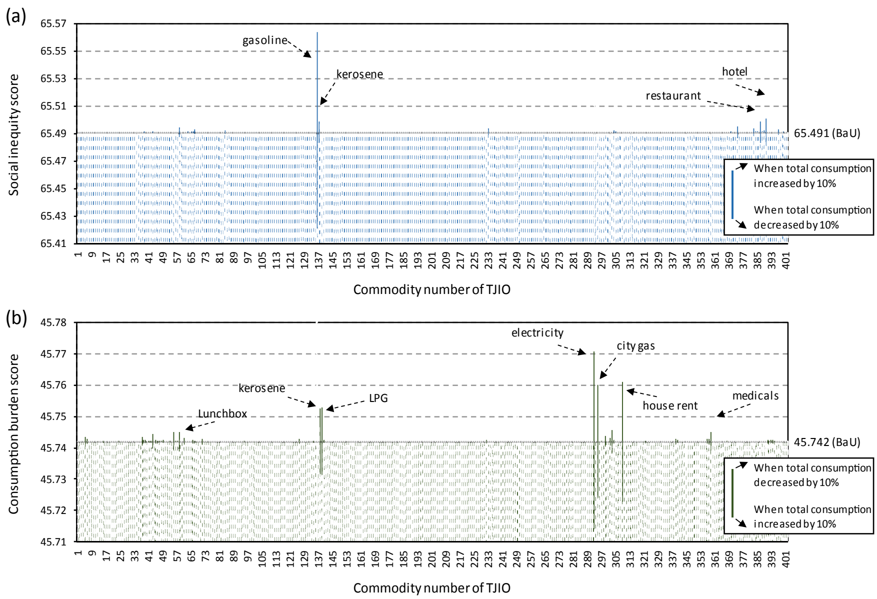

Fig. 34.4 Consumption based sensitivity of social inequity (**a**) and consumption burden scores (**b**)

of changes in future consumption burden and social inequity scores, cognizant of stakeholder priorities and shifting demographics.

An added benefit of this approach is not only the determination of 'scores' but also the ability to look inside the scores and determine which specific goods and services which generate the highest levels of public bads under changing consumption patterns and the groups responsible for their generation (Chapman and Shigetomi 2018). Figure 34.4 details sensitivity analysis of social equity and consumption burden scores according to a change in consumption of individual commodities up to (positive and negative) 10%.

A shown in panel a, social inequity scores are impacted heavily by gasoline and kerosene consumption and the use of hotel and restaurant related services. Alternatively, as shown in panel b, consumption burden scores are influenced by variations in household energy types including electricity, city gas, LPG and kerosene. On the service side, food and medical services have a prominent role. Understanding current stakeholder preferences and influential types of consumption allows for the shaping of policy to meet stakeholder preferences and achieve environmental and sustainability goals.

The proposed research methodology has some limitations, foremost among them is the constant consumption patterns from the year 2005 which are applied to future footprint projections. While this approach allows us to realize the impacts of demographic shifts, it is also important to understand future footprint intensities, consumption pattern changes and potential policy interventions.

Additionally, although the goal of the research is to determine social inequity outcomes based on domestic household footprints and preferences, underpinning assumptions rely on global norms in some cases (Miller and Blair 2009) and precedential research identifies a potential footprint quantification variance of around 20%, dependent on the model employed (Min and Rao 2018). Finally, the method employed to determine stakeholder proactiveness based on preferences expressed in a national survey is in the early stages of development and we recognize that environmental awareness does not necessarily translate into pro-environmental behavior (Wang et al. 2011).

34.5 Conclusions

The IOSEF is a novel sustainability assessment framework which considers both energy justice and lifecycle perspectives, allowing for the evaluation of policy implications to improve social equity with respect to both demographic structures and household consumption patterns. By estimating virtual household footprints for GHG emissions, industrial waste generation, green and blue water, the mining risk for critical materials needed for low-carbon technologies and primary particulate matter ($PM_{2.5}$) this study confirmed that social inequity derived from these footprints might be better mitigated in line with stakeholders' participation and probable behavior preferences. The approach outlined in this study offers multiple benefits to policy makers, as follows:

First, it allows for the identification of future consumption trends, footprint quantification, an evaluation of overall social inequity levels and allocation of household consumption burdens.

Second, the twin dimensions of social inequity and consumption burden score expression allow for comprehensive policy making cognizant not only of the benefit derived from reduced footprints, but also of a societally desirable level of public bad origin and subsequent burden allocation. Toward improving social equity, typically a burden allocation toward households in higher income brackets is considered desirable in order to reduce the gap between rich and poor (vertical equity; (Mooney and Stephen 1997)), subject to stakeholder preferences.

Third, in combination with stakeholder input, key environmental policy issues can be clarified relevant to people's lifestyles. Further, by combining the outputs of the IOSEF (namely social inequity and consumption burden scores) with environmental footprints and their respective make-up, hot spots for policy redress can be identified alongside priority SDGs.

Fourth, considering the linkages between footprints, demographic trends and stakeholder preferences, issues of urgency in terms of specific footprint actions or undesirable demographic shifts which cause imbalance can be identified.

Considering the evidence base investigated, input-output analysis can be applied to dig deeper into footprints and identify specific products and services which impair social equity or cause inequitable allocation of burdens, particularly toward lower income groups. Considering that there is no one-size-fits-all policy approach, the proposed IOSEF developed in this study can be used for policy scenario analyses. The proposed tool will allow policy makers to test various approaches prior to their implementation in order to improve societal equity and consumption burden allocation outcomes in line with stakeholder preferences and cognizant of lifestyle and consumption. Finally, although there are some limitations to this study, it demonstrates the evaluation of lifestyle-based social inequity by combining direct and indirect environmental burdens (i.e. footprints) with a large sample survey examining stakeholder engagement for the first time. The described approach is also able to be applied internationally, for example utilizing the global MRIO (Lenzen et al. 2013; Tukker et al. 2013; Dietzenbacher et al. 2013), a consumer expenditure survey and weighting factors, allowing for an evaluation of and comparison between nations.

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Chapter 35
Exergy and Environmental Analysis of a Bio-Hydrogen Supply Chain Using Data Envelope Analysis

Daisuke Hara, Chiharu Misaki, Hiromu Sugihara, Seiya Kako, Noboru Katayama, and Kiyoshi Dowaki

Abstract Hydrogen is a promising fuel for fuel cell (FC) mobility use, given its high energy density and the lack of CO_2 emission from its use during the operating stage of mobility. In addition, biomass-derived hydrogen, which is carbon neutral, is an attractive fuel because its use can mitigate CO_2 emission during the hydrogen production stage. However, because of the low energy density of biomass feedstocks, they first must be effectively converted to hydrogen; an effective hydrogen use path, including hydrogen storage and mobility and FC utilization for different scale mobility, that takes into consideration the environmental impacts and exergy is needed. In this study, the entire hydrogen path (hydrogen production, hydrogen storage, and mobility) was investigated using life cycle assessment and exergy analysis to determine the corresponding environmental and exergy hotspots and an effective hydrogen path. To compare various types of functional mobility, data envelope analysis was used. It was found that metal hydride (MH) utilization was an important factor in the mitigation of environmental damages caused by using hydrogen as fuel and in the effective use of biomass feed feedstock. Also, it was indicated that the reduction of precious metals in MH and FC would be necessary to mitigate environmental impacts.

Keywords Data envelope analysis · Exergy efficiency · Life cycle assessment · Metal hydride · Fuel cell applications

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35.1 Introduction

Hydrogen is an attractive fuel alternative to fossil fuels and electricity for mobility technology. It has been estimated that the entire hydrogen demand of the world will expand from seven trillion Japanese yen in 2015 to 160 trillion Japanese yen in 2050 (NIKKEI BP Clean Tech Institute 2013). Moreover, it has also been reported that fuel cell vehicles (FCVs) will account for approximately 60.00% of the hydrogen demand in 2050 (NIKKEI BP Clean Tech Institute 2013). This supports the high expectations for hydrogen as a fuel for mobility.

Hydrogen can be produced from local resources including biomass with low energy density, scattered around an area. That is, biomass-derived hydrogen can contribute to local production for local consumption as well as the abatement of CO_2 emissions. In addition, hydrogen can be stored in tanks by various storage methods and efficiently converted into power using Fuel cell (FC) systems. FC systems can also be operated using hydrogen fuel from renewable sources. For these reasons, the promotion of FC mobility such as vehicles, forklifts, and assisted bicycles, is potentially considerably significant.

In this study, several FC utilization paths for mobility, including biomass derived hydrogen (Bio-H_2) production and storage, were assessed using life cycle assessment (LCA). Exergy analysis has also been employed because a biomass energy system involves heat loss due to thermodynamic irreversibility throughout the process and mobility should occur under atmospheric conditions. That is, it is necessary to identify the less effective subsystem.

Therefore, hydrogen fuel of woody biomass feedstock or sewage sludge origin was included in this study. As noted in our previous studies, the CO_2 equivalent intensity of Bio-H_2 use had lower global warming potential (GWP) that of woody biomass use (Kondo et al. 2018). Moreover, on-site hydrogen production using sewage sludge shows good potential due to the beneficial environmental impacts of both feedstock characteristics and lack of hydrogen transportation.

After production, hydrogen has to be stored in a tank under high- or low-pressure conditions. Considering the environmental impacts of this step, we focused on a storage system under a lower pressure condition. That is, a suitable utilization system using metal hydride (MH) was discussed. The energy density, on the basis of the total weight of H_2 being stored, is an important issue. Compared to a conventional lithium ion (Li-ion) battery, a higher compression storage tank might be necessary for the use of H_2. Inversely, the higher compression status results in damaging eco-burden because of the larger compression power. This implies that a lower pressure condition is preferable. MH is one candidate to replace a Li-ion battery and/or a compression storage tank and can mitigate GWP.

In impact analysis as part of LCA, the abiotic depletion potential (ADP) is an important index. The rare metals, platinum and/or nickel and others, used in FC systems impact the ADP index of the system. In addition, according to previous research, the ADP and other environmental impact categories are similar in terms of platinum's placement in each impact category (Duclos et al. 2017). That is, platinum can be a representative indicator of other impact categories. Thus, here, ADP was considered.

To summarize our research plan, we considered the Bio-H_2 utilization paths, including possible applications, in terms of the eco-burden, using LCA and exergy analysis. For each path, finding the more effective path and environmental and energic hotspots was our purpose. However, we needed to characterize each path because of the combination of evaluated indexes. Therefore, we used data envelope analysis (DEA) to compare the various types of functional mobility.

35.2 Target System and Methodology

35.2.1 System Boundary and Functional Unit

In this study, the entire hydrogen path from biomass feedstock to mobility utilization was investigated using exergy analysis, LCA, and DEA. More specifically, it was assumed that hydrogen paths consist of three phases: hydrogen production (woody biomass and sewage sludge), hydrogen storage (compressed hydrogen and MH), and mobility (cars, bicycles, and forklifts). Twelve paths with various combinations of hydrogen production, hydrogen storage, and mobility, were analyzed. In addition, to compare the GWP values of the hydrogen paths, the conventional cases (gasoline car (GC), Li-ion assisted bicycle (LB), diesel forklift (DF)) were analyzed using LCA as well. Table 35.1 shows the 12 hydrogen paths. The details of each phase are explained later in this paper. Figure 35.1 shows the target system of this study.

The evaluation unit of this study (the so-called functional unit in LCA) is depreciation durable years for each mobility (Car: 6 years, Bicycle: 2 years, Forklifts: 4 years) (Tokyo Metropolitan Government Bureau of Taxation 2019).

35.2.2 Life Cycle Assessment (LCA)

LCA is an environmental impact assessment methodology based on ISO 14040 and 14044.

In this study, the impacts of each hydrogen path and conventional case on GWP and ADP were assessed using Simapro software Ver. 8.5.0.0. The background data were derived from Ecoinvent 3 and a CML model was used as an environmental impact assessment method. Note that we ignored the construction of hydrogen plants and mobility. Platinum, the catalyst for FC, has a great environmental impact, and was, therefore, considered even though it is included in the FC construction phase (Duclos et al. 2017).

Table 35.1 Hydrogen paths

Path	Hydrogen production	Hydrogen storage	Mobility
A	Woody biomass	Metal hydride	Car
B	Woody biomass	Hydrogen compression	Car
C	Sewage sludge	Metal hydride	Car
D	Sewage sludge	Hydrogen compression	Car
E	Woody biomass	Metal hydride	Bicycle
F	Woody biomass	Hydrogen compression	Bicycle
G	Sewage sludge	Metal hydride	Bicycle
H	Sewage sludge	Hydrogen compression	Bicycle
I	Woody biomass	Metal hydride	Forklift
J	Woody biomass	Hydrogen compression	Forklift
K	Sewage sludge	Metal hydride	Forklift
L	Sewage sludge	Hydrogen compression	Forklift

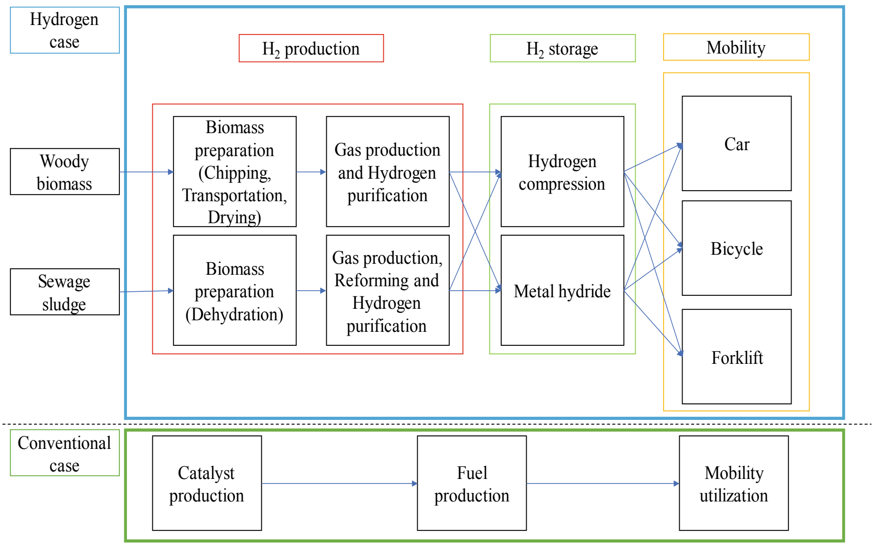

Fig. 35.1 System boundary (Kondo et al. 2018)

35.2.3 Exergy Analysis

Exergy analysis is an energy assessment methodology that can evaluate the maximum effective energy of a target system. The advantage of exergy analysis is that we can assess the maximum effective energy and the energy loss caused by an entropy increment because exergy analysis is based on both the first and second laws of thermodynamics (Kondo et al. 2018). This means of assessment based on the maximum effective energy and energy loss is important for understanding biomass-derived hydrogen, whose feedstocks have low heating values and should be effectively used. Thus, the total exergy efficiency of each hydrogen path was investigated. Exergy can be chemical or physical, as follows:

$$\mathbf{Ex} = \mathbf{Ex_{ch}} + \mathbf{Ex_{ph}} \tag{35.1}$$

where $\mathbf{Ex}$ is the total exergy of target system, $\mathbf{Ex_{ch}}$ is the chemical exergy, and $\mathbf{Ex_{ph}}$ is the physical exergy. The chemical exergy and physical exergy are expressed as Eqs. (35.2) and (35.3) as follows:

$$\mathbf{Ex_{ch}} = \sum_{\mathbf{i}} \mathbf{n_i}\left(\mathbf{e}_{0_i} + \mathbf{RT}_0\mathbf{ln}\frac{\mathbf{n_i}}{\sum \mathbf{n_i}}\right) \tag{35.2}$$

$$\mathbf{Ex_{ph}} = \sum_{\mathbf{i}} \mathbf{n_i}[\mathbf{h_i} - \mathbf{h}_0 - \mathbf{T}_0(\mathbf{s_i} - \mathbf{s}_0)] \tag{35.3}$$

where $\mathbf{n_i}$ is the mol yield of gas i [mol/kg], $\mathbf{R}$ (= 8.3145) is the gas constant [J/molK], and $\mathbf{e}_{0_i}$ is the standard chemical exergy [KJ/mol], $\mathbf{T}_0$ is the reference temperature [K] (= 298.15) $\mathbf{h}$ and $\mathbf{s}$ are the enthalpy and entropy of a certain temperature, and $\mathbf{h_0}$ and $\mathbf{s_0}$ are the enthalpy and entropy under standard conditions, respectively.

The exergy efficiency is defined as Eq. (35.4) as follows:

$$\boldsymbol{\varepsilon} = \frac{\mathbf{Ex_R}}{\mathbf{Ex_{in}}} \tag{35.4}$$

where $\boldsymbol{\varepsilon}$ is the exergy efficiency, $\mathbf{Ex_R}$ is the effective exergy from the target system, and $\mathbf{Ex_{in}}$ is the input exergy of the target system.

In this study, the entire exergy efficiency of each hydrogen path was calculated using Eq. (35.5) as follows:

$$\boldsymbol{\varepsilon}_{entire} = \boldsymbol{\varepsilon}_p * \boldsymbol{\varepsilon}_s * \boldsymbol{\varepsilon}_f \tag{35.5}$$

where $\boldsymbol{\varepsilon}_{\mathbf{entire}}$ is the exergy efficiency of the entire hydrogen path, $\boldsymbol{\varepsilon}_{\boldsymbol{p}}$ is the exergy efficiency of hydrogen production, $\boldsymbol{\varepsilon}_{\mathbf{s}}$ is the exergy efficiency of hydrogen storage, and $\boldsymbol{\varepsilon}_{\boldsymbol{f}}$ is the exergy efficiency of the FC used for mobility.

35.2.4 Data Envelope Analysis

DEA is a nonparametric assessment methodology used in operations and economics research to estimate production frontiers. Specifically, DEA can assess comprehensive efficiency using both output parameters (the results of a certain organization's business or products) and input parameters (the resources used to obtain the results) (Sato et al. 2018). That is, the smaller the input parameter's values are and the larger the output parameter's values are, the more efficient a certain process is. In this manner, DEA does not compare merely how small or large the input or output parameters are but uses the relative efficiency calculated from both the input and output parameters. Thus, DEA can be used to compare the different types of functional mobility. Another advantage of DEA is that it allows the integration of multiple indicators into a single indicator as a relative efficiency value. For example, previous research integrates the performance and environmental impacts of a household FC cogeneration system into one efficiency value using DEA (Sato et al. 2018).

In this study, DEA was used to compare 12 paths with different functional units. Using DEA, the hydrogen paths were assessed via the integrated indicator of exergy efficiency and LCA results.

The input parameters are the amount of biomass, ADP, and ADP (fossil fuels). The amount of biomass can represent the heating value difference between woody biomass (13.23 MJ (Kondo et al. 2018)) and sewage sludge (12.75 MJ, Dry-basis). In addition, ADP (fossil fuels) can represent the differences between plant-scale hydrogen production (woody biomass) and on-site hydrogen production (sewage sludge) because the latter does not include transportation of feedstock and hydrogen. In this scenario, fossil fuels need not be used for transportation. The output parameters are the total exergy efficiency and the GWP value of the hydrogen path.

The efficiency DEA was calculated using linear programming problems as follows (Sato et al. 2018):

<Objective function>

$$\max\boldsymbol{\theta} = \mathbf{u}_1\mathbf{y}_{1\mathbf{k}} + \mathbf{u}_2\mathbf{y}_{2\mathbf{k}} \cdots + \mathbf{u}_\mathbf{n}\mathbf{y}_{\mathbf{nk}} \tag{35.6}$$

<Constraint expression>

$$\mathbf{v}_1\mathbf{x}_{1\mathbf{k}} + \mathbf{v}_2\mathbf{x}_{2\mathbf{k}} \cdots + \mathbf{v}_\mathbf{m}\mathbf{x}_{\mathbf{mk}} = 1 \tag{35.7}$$

$$\begin{aligned}&\mathbf{u}_1\mathbf{y}_{1\mathbf{k}} + \mathbf{u}_2\mathbf{y}_{2\mathbf{k}} \cdots + \mathbf{u}_\mathbf{n}\mathbf{y}_{\mathbf{nk}}\\ &\quad \le \mathbf{v}_1\mathbf{x}_{1\mathbf{k}} + \mathbf{v}_2\mathbf{x}_{2\mathbf{k}} \cdots + \mathbf{v}_\mathbf{m}\mathbf{x}_{\mathbf{mk}}\end{aligned} \tag{35.8}$$

$$\mathbf{v}_1, \mathbf{v}_2, \cdots \mathbf{v}_\mathbf{m} \geq 0 \tag{35.9}$$

$$\mathbf{u}_1, \mathbf{u}_2, \cdots \mathbf{u}_\mathbf{n} \geq 0 \tag{35.10}$$

where $\boldsymbol{x}_i$ ($\mathbf{i} = 1, 2, \cdots \mathbf{m}$) is the input value; $\mathbf{y_j}$ ($\mathbf{j} = 1, 2, \cdots \mathbf{n}$) is the output value; $\mathbf{v_i}$ ($\mathbf{i} = 1, 2, \cdots \mathbf{m}$) and $\mathbf{u_j}$ ($\mathbf{j} = 1, 2, \cdots \mathbf{n}$) are the input and output weight values, respectively; and k is the number of scenarios.

The maximum value of the objective function is 1.00 because of Eqs. (35.7) and (35.8). Thus, the most effective scenario exists when the objective function is 1.00. Three input parameters and two output parameters were assumed. These were substituted into i and j, respectively.

35.2.5 Hydrogen Demand of Each Type of Mobility

To evaluate environmental impacts using LCA, first the hydrogen demand for each mobility were determined. The rated output or input data, heating value of each fuel, and other engine and battery efficiencies were obtained (Ministry of Land, Infrastructure, Transport and Tourism, "Fuel efficiency best 10 by vehicle weight category," Available: http://www.mlit.go.jp/common/001284635.pdf; Fuc et al. 2016; YAMAHA 2005; Ikeya et al. 2015; Zheng et al. 2015; Saw et al. 2016; TOYOTA, "The MIRAI Life Cycle Assessment for communication"Available: http://www.gronabilister.se/toyota-mirai-lca.pdf?cms_fileid=9b81589a2a7ae33e34936c3de80b4c51; "Fuel cell forklift catalog" 2010; Yamate et al. 2018). Using these data, the rated theorical output or input was calculated via the engine efficiency and fuel heating value. Then, based on the rated output data, heating value of hydrogen, and energy conversion efficiency of FC, the hydrogen input was estimated. Using this procedure, the output of both the FC mobility and conventional cases turned out equal. Figure 35.2 shows this procedure (red-colored values are primary data).

In addition, the annual hydrogen demand was calculated (TOYOTA, "The MIRAI Life Cycle Assessment for communication"Available: http://www.gronabilister.se/toyota-mirai-lca.pdf?cms_fileid=9b81589a2a7ae33e34936c3de80b4c51), (Zyun 2010; Shizuoka Komatsu Forklift Co., Ltd 2019; Inagaki et al. 2011; Hosseinzadeh et al. 2013; Kovač and Paranos 2019). Using these data and the hydrogen input and annual hydrogen demand, the hydrogen input per functional unit for each type of mobility was calculated. It was assumed that a forklift here operates with a 1.00 ton-payload. Table 35.2 shows the data to calculate the annual hydrogen demand.

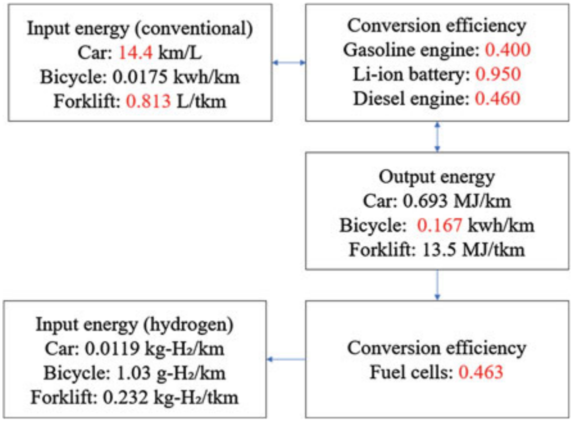

Fig. 35.2 Output estimation

Table 35.2 Data sets used to estimate hydrogen demand

	Car	Bicycle	Forklift	Unit
Velocity	6.000E+01	1.440E+01	1.080E+01	km/h
Annual travel distance	1.000E+04	2.400E+03	1.056E+03	km/year
H_2 demand	1.567E+02	2.470E+00	2.641E+03	kg/year

35.3 Inventory Analysis

During the inventory analysis, the inputs and outputs of each sub-system were investigated. Here, the means to investigate inventory data for each phase (hydrogen production, hydrogen storage, FC mobility and conventional cases) are explained.

35.3.1 Hydrogen Production from Woody Biomass

The inventory data and exergy efficiency are cited from (Kondo et al. 2018). In this study, Japanese cedar was converted into hydrogen using two-step pressure-swing adsorption (PSA), which aims to reduce the work required during the conventional PSA process. The system involves five processes: chipping, transportation, drying, syngas production, and hydrogen purification. The plant was designed under a steady state at a plant scale of 12.00 t-dry/day, annual operating hours of 7200.00 h/year, and an S/C of 1.00. Inventory data with a functional unit 1.00 kg-hydrogen is reported. Thus, we used this data, assuming a linear relationship between the hydrogen amount and other inventory data. It is also reported that CO_2 emitted from the hydrogen plant can be recovered owing to its utilization for agricultural purposes (Kondo et al. 2018).

35.3.2 Hydrogen Production from Sewage Sludge

The authors investigated the inventory data and exergy efficiency using Aspen Plus (Aspen plus Ver 9.1). In this model, the sewage sludge is converted into hydrogen immediately next to a household (on-site) using two-step PSA. Thus, it is expected that this system can mitigate environmental impacts because of the lack of transportation of feedstock and hydrogen. The whole system involves three processes: production, reforming, and two-step PSA. Inventory data with a functional unit 1.00 Nm^3-hydrogen was investigated. Thus, we used this data assuming a linear relationship between the hydrogen amount and other inventory data. Because it is reported that CO_2 emitted from hydrogen purification using two-step PSA can be recovered due to its use in agriculture, CO_2 recovery was considered in this study (Kondo et al. 2018). However, the amount of CO_2 recovered from this process is smaller than that recovered from the woody biomass process according to our simulation results (5.47 kg-CO_2/kg-H_2).

35.3.3 Hydrogen Storage Using Hydrogen Compression

Here, the inventory data and exergy efficiency of hydrogen compression or expansion were calculated. After hydrogen production using two-step PSA, the hydrogen was at 0.4000 MPa (Kondo et al. 2018). Thus, hydrogen needed to be compressed or expanded for transportation or storage in each type of mobility. In the hydrogen paths including hydrogen production from woody biomass, the transportation from the plant to a hydrogen refueling station was included. The distance from the plant to the hydrogen refueling station was assumed to be 27.50 km, which is the same distance as that required for woody biomass transportation (Kondo et al. 2018).

Before hydrogen transportation from a woody biomass plant, hydrogen was compressed from 0.4000 MPa to 20.00 MPa; after transportation, hydrogen was compressed or expanded to the filling pressure for each type of mobility (Car: 70.00 MPa, bicycle: 3.00 MPa, Forklift: 35.00 MPa) (TOYOTA, "The MIRAI Life Cycle Assessment for communication"Available: http://www.gronabilister.se/toyota-mirai-lca.pdf?cms_fileid=9b81589a2a7ae33e34936c3de80b4c51; "Fuel cell forklift catalog" 2010) (Kovač and Paranos 2019). Also, it was assumed that hydrogen is cooled or warmed before transportation (298.15 K) and use for a type of mobility (233.15 K) (Technova Co., Ltd. 2019). On the other hand, in the case of hydrogen paths with sewage sludge hydrogen production, hydrogen was directly compressed from 0.4000 MPa to the filling pressure for each type of mobility because hydrogen was produced on-site.

The work to compress or expand hydrogen was calculated using the transmission, mechanical, and adiabatic efficiencies and the enthalpy data before and after compression or expansion (Takahashi 1976; National Institute of Standards and Technology 2019). After the calculation of the compression or expansion work, exergy analysis was conducted using Eqs. (35.1)–(35.5).

35.3.4 Hydrogen Storage Using MH

The MH used in this study was $LmNi_{4.73}Mn_{0.12}Al_{0.1}$. Here, the authors investigated the relationship between the MH weight and the amount of hydrogen stored and discharged in MH experimentally. These experimental data were used to determine the amount of MH needed for each mobility and the amount of hydrogen that can be stored in that amount of MH. Figure 35.3 shows this relationship. According to these regression lines, the amount of MH used in each mobility are 349.75 (car), 8.21 (bicycle), 91.24 (Forklift) kg-MH respectively (TOYOTA, "The MIRAI Life Cycle Assessment for communication"Available: http://www.gronabilister.se/toyota-mirai-lca.pdf?cms_fileid=9b81589a2a7ae33e34936c3de80b4c51; "Fuel cell forklift catalog" 2010) (Pragma industries 2019).

The storage experiment was completed under a condition (273.15 K and 0.4000 MPa) for easy storage of hydrogen. However, the hydrogen discharge experiment was completed under standard conditions. From Fig. 35.3, it can be seen that all the hydrogen stored in the MH cannot be discharged (approximately 6.52% hydrogen remained in the MH). Therefore, the hydrogen paths, including MH, need to produce an extra amount of hydrogen.

In this study, the exergy loss of the hydrogen paths, including the hydrogen production from woody biomass, was considered because hydrogen should be compressed for transportation. However, the exergy loss of hydrogen storage and discharge from MH was not considered because we used the complicated MH ($LmNi_{4.73}Mn_{0.12}Al_{0.15}$) and could not obtain accurate chemical exergy data for this

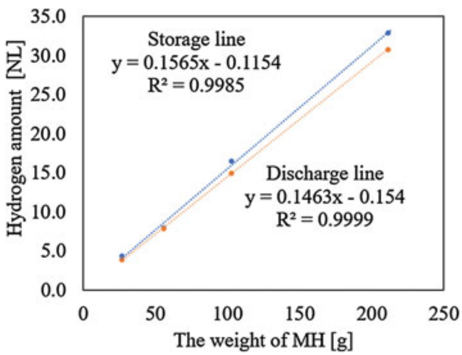

Fig. 35.3 Discharge and storage regression lines

MH. In addition, it has been reported that a hydrogen storage system using MH does not lead to significant exergy loss (Thattai et al. 2016). For these reasons, to prevent the uncertainty in the MH exergy, the exergy loss of MH was not considered.

35.3.5 Mobility Using FC

In this study, a car, bicycle, and forklift were assumed to be the final hydrogen demand application. The FC scale loading for each mobility was cited or estimated (Car: 114.00, Bicycle: 0.2400, Forklift: 35.70 kW) (YAMAHA, PAS AMI Toriatsukai Setsumeisho [PAS AMI user's manual]: Yamaha Motor Co., Ltd) (TOYOTA, "The MIRAI Life Cycle Assessment for communication"Available: http://www.gronabilister.se/toyota-mirai-lca.pdf?cms_fileid=9b81589a2a7ae33e34936c3de80b4c51; Fuel cell forklift catalog 2010). Note that the FC scale loading on the forklift was calculated using the 0.6 rule because the data of the FC scale is a 2.50 ton-maximum payload in reference No. 14 but the scale we assumed in this study is a 3.00 ton-maximum payload ("Fuel cell forklift catalog" 2010). This FC scale data was nearly validated by the rated output of the diesel forklift (EUROLIFT 2019). Based on these data of FC scales, the amount of platinum catalyst in each FC was calculated using the 0.6 rule which has been used in previous studies (Car: 0.1286, Bicycle: 0.0032, Forklift: 0.0641 kg) (Sato et al. 2018) (Mizuho Information & Research Institute Inc 2008).

35.3.6 Conventional Case

To compare the greenhouse gas (GHG) values of the hydrogen paths, the conventional cases (gasoline car, Li-ion assisted bicycle, and diesel forklift) were analyzed using LCA in terms of GWP values. The data were obtained from Ecoinvent 3 and previous research studies (Fuc et al. 2016) (Nanaki and Koroneos 2012). Because we considered the platinum catalyst of the FC in our study, its use in conventional cases was analyzed to match the system boundary.

35.4 Results and Discussion

35.4.1 LCA Results

Table 35.3 shows the LCA results of each hydrogen path and conventional case.

The ADP value is nearly the same for the same mobility. This is because the platinum catalyst used in FC mobility accounts for most of the influence on the ADP value. As in previous studies, platinum also has a negative effect on other impact categories in LCA (Duclos et al. 2017).

In addition, comparing within the same mobility, the hydrogen paths which includes the woody biomass hydrogen production are always better than the sewage sludge process in terms of GWP because of the CO_2 recovery.

Comparing hydrogen paths of the same production method and the same mobility, those using MH storage are always better than those using hydrogen compression in terms of GWP value. This indicates that MH can contribute to GWP mitigation because MH does not require the work needed to compress hydrogen.

In summary, the decrease in the platinum catalyst in a FC mobility would be important to mitigate the environmental impacts on ADP as well as other impact categories. In addition, the MH utilization during the hydrogen storage phase can lower the GHG value because of the lack of hydrogen compression power.

Table 35.3 LCA results

Path	Bio-mass amount	ADP	ADP (fossil fuels)	GWP
Unit	kt	kg Sb eq	GJ	kg CO_2 eq
A	2.139E-02	2.960E-01	1.918E+02	-4.330E+03
B	2.000E-02	2.969E-01	2.311E+02	3.435E+02
C	2.161E-02	2.969E-01	1.776E+02	9.562E+03
D	2.020E-02	2.990E-01	2.753E+02	1.818E+04
GC	–	–	–	2.357E+03
E	1.123E-04	4.968E-03	1.793E+00	5.059E+01
F	1.050E-04	4.967E-03	1.982E+00	7.366E+01
G	1.135E-04	4.968E-03	1.719E+00	1.235E+02
H	1.061E-04	4.969E-03	1.804E+00	1.328E+02
LB	–	–	–	6.442E+01
I	2.403E-01	1.893E-01	1.753E+03	-8.687E+04
J	2.247E-01	1.851E-01	2.091E+03	-4.267E+04
K	2.428E-01	1.995E-01	1.594E+03	6.923E+04
L	2.270E-01	2.048E-01	2.384E+03	1.406E+05
DF	–	–	–	4.771E+04

35.4.2 Exergy Efficiency

Here, the exergy efficiency of each phase was calculated. Using these results, the entire exergy efficiency of each hydrogen path was calculated as well.

The exergy efficiency data of the hydrogen production phases is cited from previous research (Kondo et al. 2018). Table 35.4 shows the exergy efficiency of hydrogen production by feedstock.

During the hydrogen storage phase, the exergy efficiency of hydrogen compression for each path was determined as shown in Table 35.5.

During the mobility phase, the exergy efficiency of the FC is 0.5272 which is calculated under the FC conditions of an operating voltage of 0.6500 V and an electromotive force of 1.180 V.

Table 35.6 shows the exergy efficiency of each path. All the paths using MH are more efficient than that using hydrogen compression when comparing the hydrogen paths to the same hydrogen production method and the same mobility.

It can be said that the hydrogen storage method using MH is an effective storage means from the viewpoint of energy-effective utilization.

Table 35.4 Exergy efficiency of the hydrogen production phase from woody biomass and sewage sludge (Kondo et al. 2018)

Feedstock	Exergy efficiency
Woody biomass	0.4100
Sewage sludge	0.3535

Table 35.5 Exergy efficiency of the hydrogen storage phase for each hydrogen path including hydrogen compression

Path	Exergy efficiency
A	0.7885
C	0.7322
E	0.7927
G	0.9062
I	0.8059
K	0.7816

Table 35.6 Path exergy efficiency

Path	Exergy efficiency	Path	Exergy efficiency
A	0.2162	G	0.1864
B	0.1705	H	0.1689
C	0.1864	I	0.2162
D	0.1365	J	0.1742
E	0.2162	K	0.1864
F	0.1714	L	0.1457

Table 35.7 DEA final results

Path	DEA result	Path	DEA result	Path	DEA result
A	0.04378	E	1.000	I	1.000
B	0.09473	F	1.000	J	0.6927
C	0.01673	G	1.000	K	0.02575
D	0.01216	H	0.9086	L	0.01896

35.4.3 DEA Results

Table 35.7 shows the DEA final results.

Overall, the hydrogen paths including the hydrogen production from woody biomass is better than that including the sewage sludge process.

In addition, comparing the DEA results that have the same means of hydrogen production and FC mobility, the hydrogen paths using MH were found to be better than those using hydrogen compression except for the car case (Path A, B). Note that the weight increment caused by the MH was not considered in this study.

Paths E, F and G are the most effective in the analysis of bicycle results. However, the DEA results of Path H is also close to 1.000. Thus, these paths also have the potential to be introduced as hydrogen paths of a FC bicycle.

Path I is also the most effective in the analysis of forklift results (I-L). This means the introduction of woody biomass-derived hydrogen into the MH hydrogen forklift process is the best hydrogen path balancing both exergy efficiency and environmental impacts. Also, it is found that the hydrogen paths including hydrogen production from woody biomass (Path I, J) are considerably more efficient than the paths including sewage sludge processes (Path K, L) thanks to the large amount of CO_2 recovery caused by the large demand of hydrogen.

In reviewing the car results, all paths resulted in poor efficiency values. Thus, these processes have a low potential compared to other paths.

35.5 Conclusion

Product efficiency of the 12 hydrogen paths was compared. This included evaluation of each path's exergy efficiency and environmental impacts using DEA methodology,

We obtained the following significant results: (1) Low-pressure storage in the use of MH has good potential to mitigate environmental impacts, (2) the exergy efficiency in the case of MH mobility would be more advantageous, (3) small-scale mobility (bicycle) with MH storage would obtain the maximum product efficiency (Path E, G), and (4) the forklift with MH, which is fueled by Bio-H_2 of woody biomass origin, would also obtain the maximum product efficiency (Path I).

These results indicate that the aspect of MH utilization is an important factor for the mitigation of adverse environmental impacts. Also, the effective use of biomass feedstock with a low energy density would be achieved.

However, there are several problems to solve before introducing the MH mobilities. For instance, the gain of total weight due to MH would influence performance. That is, the relationship between the total weight and the fuel economy is extremely important. In general, an increase in weight leads to a decrease in performance. Thus, it is necessary to investigate this influence and its potential countermeasures.

Moreover, in this study, the continuous discharge flow rate from the storage tank was assumed to be ensured. However, we know that the discharge would be affected by the configuration of a tank, the packed conditions, and the operating conditions of temperature and inner pressure. Especially, H_2 discharge from MH is an endothermic reaction with the temperature drop of MH (Chung et al. 2013). This implies that the suitable design of a tank, the appropriate operating conditions and the countermeasure of continuous flow (e.g. heat supply from flue gas from FC) shall be found out. So far, we fabricated the experimental apparatus, and are testing for evaluating H_2 flow rate varying the experimental conditions including the replacement of MH species.

Finally, the reduction of precious metals used in MH and FC would be necessary because they strongly influence the environmental impact of the ADP category. For instance, the R&D of a fuel cell with a small amount of platinum being is carried out, and the cell without any efficiency loss and with gains in current density is likely to be developed. We will continue to monitor such a cell's development incorporate this technology in future studies accordingly.

In the future, these factors will be implemented through demo tests for use in the experimental mobility, using simulation analysis, and/or other methods.

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Chapter 36
The Readiness Levels of Japan Supported Biomass Energy Conversion Technology Development Projects in Emerging Southeast Asia: Verification of the J-TRA Results

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Abstract We compared the readiness levels of Japan supported biomass energy conversion technology development projects in emerging Southeast Asia measured with two different methodologies; (1) levels as stated by the project fund provider, and (2) Technology Readiness Assessment (J-TRA) method. Results show that while the first method could tell the general idea about a technology development progress, the Technology Readiness Level (TRL) of J-TRA is better at indicating the project bottlenecks.

Keywords Biomass energy · Southeast asia · J-TRA · Technology readiness · Japan technology

36.1 Introduction

Japan's strategy in diversifying its energy supply including from biomass (METI, Cabinet decision on the new strategic energy plan (provisional translation) 2014) and Southeast Asia's high rate of traditional use of biomass energy (IEA 2017) has created a situation where many technology development projects for biomass energy conversion flourished in the emerging Southeast Asia region under the support of Japanese organizations and Japanese private companies (Asia Biomass Office 2013). These projects vary in terms of the feedstock type and technology type. They also exist in different levels of readiness (Ihara et al. 2019). To understand about the readiness of these technology development projects, we have established a database of projects that took place in Thailand, Indonesia, Viet Nam, Philippines, Myanmar, Malaysia, Cambodia, and Laos that received support from Japan, by collecting information manually from open and semi-open (accessible through registration) data online.

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Most of the projects were registered in the database of Japan International Cooperation Agency (JICA), New Energy and Industrial Technology Development Organization (NEDO), and Global Environment Centre Foundation (GEC), and various Japanese companies' websites. To ensure that the projects are up-to-date, we included only those taken place after the year 2010. From about 150 projects found on the websites, we double checked to ensure that they are all actually different projects. In the end, there are 86 eligible projects in our database. In our previous study, we analyzed the readiness level of these projects by using our original methodology called the Japanese Technology Readiness Assessment (J-TRA) (Ihara et al. 2019), an adaptation result from the United States' Technology Readiness Assessment (TRA) (Ihara et al. 2018). In this study, we compare the J-TRA result with the common terminology used to express technology development project readiness in each of the project website for the following aims; (1) To identify which methodology is better to communicate technology readiness level, (2) To identify which methodology is better at identifying the bottleneck of the technology, and (3) To find out whether both methodologies convey the same message.

36.2 Methodology

In this study, we compared two methodologies that present the readiness level of a technology development project. The first one is the generic terms used in the original project information sources (website). We have categorized those terms into five categories: "basic research", "research experiment", "feasibility study", "pilot demonstration project", and "full-scale operation". There is no common or standardized guideline that determines the project readiness categorization among the funding organizations. The second methodology is the J-TRA method. This method has the following seven analysis sectors: market development, technology integration, technology verification, safety, commercialization, and cost or risk and each of them have several compliance-checklist. A J-TRA results could be presented in 2 ways: 1) In 8 readiness levels (as 1 to 8) called as the Technology Readiness Level (TRL), or 2) By the percentage of compliance in our checklist for each evaluation sectors. We compared the shape of the distribution curve of the projects in the five generic readiness categories, in different TRL levels, and in percentage of J-TRA checklist-compliance, to determine their similar/dissimilarities.

36.2.1 Conversion of Project Readiness Level Terminology

Although the original terms used by the project fund providers slightly vary, they indicate similar ideas that could be translated to the generic terms as shown in Table 36.1. For example, "basic research", "networking", and "methodology proposal" could be

Table 36.1 Conversion of project readiness level terminology

Readiness level in the original names used by fund provider	Readiness level in generic terms
Basic research	Basic research
Capacity building/Networking	
Methodology proposal	
Research experiment	Research experiment
Feasibility study	Feasibility study
Feasibility survey	
Project planning study	
Pilot demonstration project	Pilot demonstration project
Demonstration project	
Model project	
Full scale	Full scale operation
Full scale operation	
Full scale demonstration project	

categorized as "basic research", while "feasibility study", "feasibility survey", and "project planning study" could be categorized as "feasibility study".

36.2.2 The J-TRA Methodology

The development and the complete application procedure of J-TRA Methodology have been explained in our previous publication (Ihara et al. 2019) (Ihara et al. 2018) (Pang et al. 2019). In the methodology, there are seven parameters to determine the readiness level of a project, and in each parameter, there is a compliance checklist. These parameters are the following; (A) Market, (B) (Technology) Development, (C) (Technology) Integration, (D) Verification, (E) Safety, (F) Commercialization, and (G) Cost and risk. The full description of the compliance checklist for all of the parameters could be found in the manual published by the Japanese Ministry of Environment (Japan Ministry of Environment 2014). The result of J-TRA could be presented either by the percentage of how many items in the checklist are fulfilled or by the Technology Readiness Level (TRL). To determine the TRL of a project, the scoring matrix shown by Table 36.2 is used. Only when all the items in each TRL is satisfied, a project can be scored as the corresponding TRL.

Table 36.2 TRL scoring matrix

TRL	A (Market)	B (Development)	C (Integration)	D (Verification)	E (Safety)	F (Commercialization))	G (Cost and risk)
1	A-1	B-1		D-1			
2	A-2	B-2		D-2			
3	A-3	B-3	C-1	D-3	E-1	F-1	G-1
4	A-4	B-4	C-2	D-4	E-2	F-2	G-2
	A-5						
5	A-6	B-5	C-3	D-5	E-3	F-3	G-3
6	A-7	B-6	C-4	D-6	E-4	F-4	G-4
7	The equipment and systems have been finalized. Manufacturing and introduction processes has been completed						
8	Manufacturing and introduction processes has been completed and is in the stage of mass production of products						

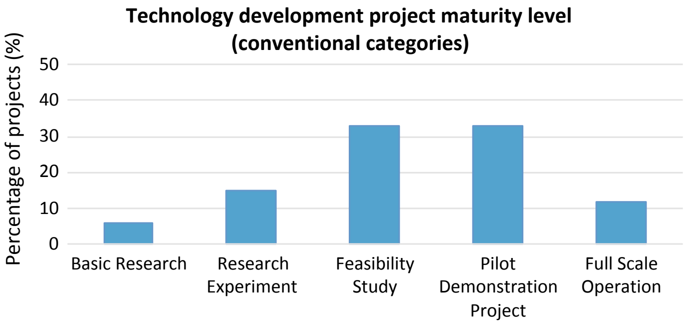


Fig. 36.1 Project readiness levels in generic terms

36.3 Results

36.3.1 Project Readiness Level in Generic Terms

After converting the terminology used in the website of the project provider, we grouped the projects into the generic terms of readiness levels; "basic research", "research experiment", "feasibility study", "pilot demonstration project", and "full scale operation". The summary of the grouping of results is shown by Fig. 36.1. The results show that about 33% of the projects are in feasibility study and pilot demonstration project levels. While these are not high, projects in the other categories are much lower. For example, projects that are running in full scale operation only make up to about 17% of all projects. Among that, there are various types of technologies (biorefinery, anaerobic digestion, boiler-turbine-generator, gasification, and carbonization).

36.3.2 J-TRA Results Based on the Percentage of Checklists Compliance

Although it is not the practice of the original American TRA, the J-TRA results could be presented based on the percentage of compliance against the checklist in each of the 7 J-TRA parameter categories. An example of the checklist is shown in Table 36.3 for the A (Market) category. There is a set of checklists for each of parameters and the compliance of them must be backed-up with evidences in the form of reports, prototypes, or a developed model.

The full checklists could be found in the TRL manual in the Japanese Ministry of Environment's website (Japan Ministry of Environment 2014). We measured all the 86 biomass projects in our database using this method and the summary of the result is shown in Fig. 36.2. Projects that comply between 25% and 50% of the checklists is

Table 36.3 Checklist for parameter category A (Market)

Item	Concepts of question	Required evidence
A-1	Has an assumption been made on the customers for the equipment systems or users of the regional model?	Articles, reports, etc.
A-2	Have the characteristics (such as purchasing power) of users such as customers targeted for sales and consumers of regional models been examined?	Reports, analysis reports, etc.
A-3	Has a method or system been established for grasping the requirements of the target users such as customers and consumers?	Prototype parts of main configuration elements/experiment model
A-4	Have the specific contents of regulations, standards, accreditation systems, and safety standards, etc. that may be obstacles for popularization of development technology been grasped?	Limited prototype/limited regional model
A-5	Have the contents of policy goals, policy supports, official roadmap etc. that are considered to boost the development and popularization of development technology been grasped?	
A-6	Has a sales/supply system or management system that is necessary for market development been examined?	Practical prototype/limited regional model
A-7	Based on the demonstration results in the environments where they will be deployed, has a structure related to business for sale/supply etc. and development of regional models been secured?	

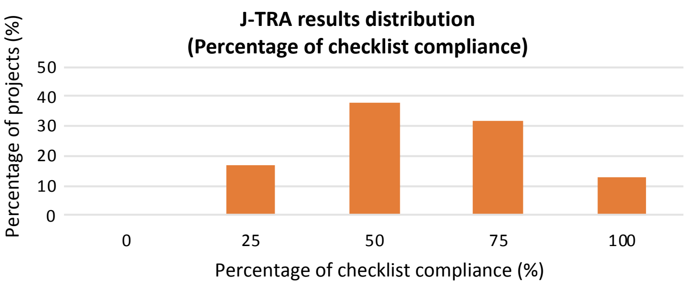


Fig. 36.2 Project readiness levels based on J-TRA checklist compliance

dominant with a little above 30% of all projects, projects that comply between 50% and 75% of the checklist is a little below 30%, while almost none of the projects is able to satisfy 100% of the checklist, there is a small number of projects that satisfy between 75% and 100% of the checklists. Among the most mature are a biorefinery project in Viet Nam, Thailand, and the Philippines, and anaerobic digestion project in the Philippines.

36.3.3 J-TRA Results Shown as TRL

Using the TRL scoring matrix shown in Table 36.2, we graded the projects against all the checklist in each J-TRA parameters. The summary of the results is shown in Fig. 36.3. Almost half of the projects were graded with TRL 2. Meaning that these projects complied to requirement A-1, A-2, B-1, B-2, D-1 and D-2 but did not comply to one or more items in the requirements for TRL 3 in the TRL scoring matrix (Table 36.2). The question of A-1 and A-2 refer to whether or not the market and location of target market have been foreseen and studied, including about their purchasing power. The question of B-1 and B-2 requirement refer to the scientific and technical elements of the technology, for example about the technology design plan appropriate for the region, personnel available for the technology development, and the specification of location for field testing. The D-1 and D-2 requirements are about paper-based verification of similar system design in the region where each of the technical components have been proven to work. While there is no identified project mature enough to be graded as TRL 8, there are a few projects that falls under the category of TRL 6. For example, an anaerobic digestion project in Thailand using animal manure and organic waste, and a gasification project in the Philippines using woody biomass.

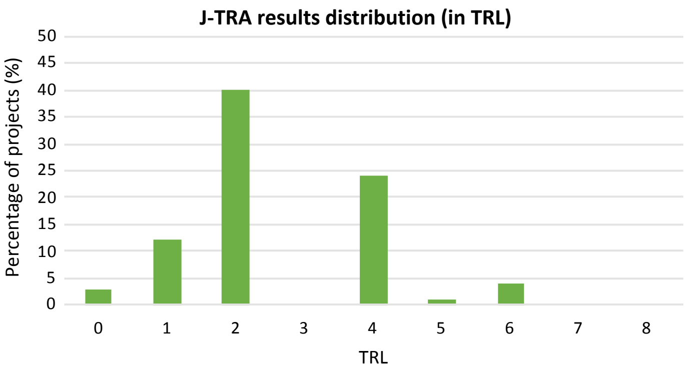


Fig. 36.3 Project readiness levels based on TRL results

To see in more detail about the projects scored with different TRL, the following sections elaborate the parameters within the TRL for different technologies being developed in each Southeast Asian country covered in this study.

Thailand

In Thailand, the most mature project found is using the biorefinery technology (Fig. 36.4). The feedstock used in this project is bagasse and located in Saraburi province in central Thailand. However, there are also projects that are biorefinery technology but still very immature such as the one using non-food biomass in Bangkok, Pathumtani which is still in the research experiment stage. Among the least mature project is pelletization using woody biomass taking place in various places such as Petchaburi and Khon Kaen.

Indonesia

Among the most mature projects in Indonesia, there is a project using Palm Oil Mill Effluent (POME) as feedstock that uses anaerobic digestion technology. The project is located in North Sumatera (GEC 2013). The project capacity is 2 MW and operating in hybrid with solar based energy generation. Based on our database, anaerobic digestion is also the most popular technology used in Indonesia with 5 out of 16 projects in the country are developing this technology. As shown in Fig. 36.5, overall, the projects are weakest in the commercialization parameter, which is key for mass production, dissemination, and cost reduction.

Viet Nam

In Viet Nam, biorefinery is the most popular technology used in the projects collected in our database. Using various types of feedstocks such as cassava and rice husks. The most mature one is a biorefinery project using cassava in Vinhoek Province,

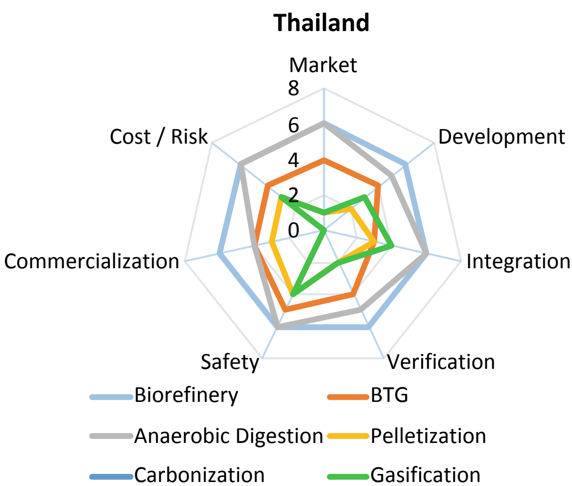


Fig. 36.4 TRL of Japan-supported biomass energy technology development projects in Thailand

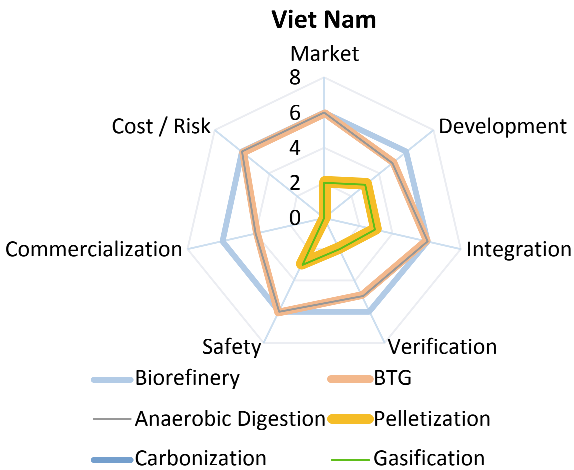
Fig. 36.5 TRL of Japan-supported biomass energy technology development projects in Indonesia

Southern Vietnam. Boiler-Turbine-Gas (BTG) is also among the most mature technology, commonly using organic industrial waste. Similar to the Indonesian situation, commercialization is also among the weakest parameter among projects in Viet Nam (Fig. 36.6).

Myanmar

The project using BTG technology in Myanmar is among the most mature one, commonly using rice husk as feedstock. While carbonization technologies (including pyrolysis and torrefaction) are quite immature and rare in other countries, in Myanmar the readiness level is on-par with a gasification project there (Fig. 36.7). These

Fig. 36.6 TRL of Japan-supported biomass energy technology development projects in Viet Nam



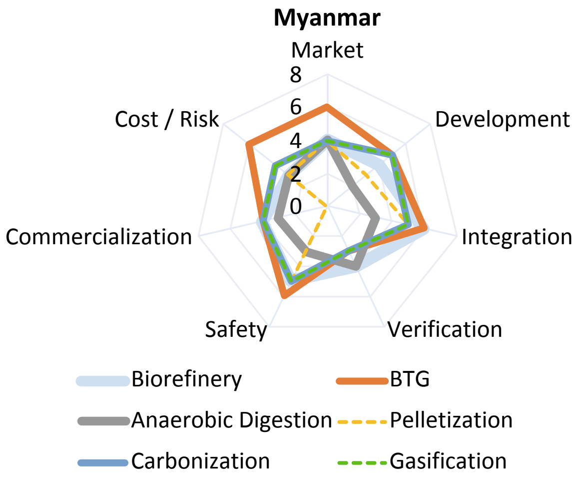


Fig. 36.7 TRL of Japan-supported biomass energy technology development projects in Myanmar

carbonization projects are found in Ayeyarwady region where many rice mills are in operation in the rice plantation area.

While commercialization parameter is similar with projects in the previous countries as one of the weakest parameters, verification is also weak in this country. The last checklists in verification parameter include whether or not the technology have undergone verification of performance in similar or actual environment and tested for CO_2 reduction effects when operating in such environment.

Philippines

In the Philippines, biorefinery is the most popular technology found among the projects in our database with 5 out of the 11 projects in the country are developing this technology (Fig. 36.8).

Malaysia

The majority of feedstocks type used in the projects in Malaysia is from Oil Palm tree (Empty Fruit Bunch (EFB), Palm Kernel Shell (PKS), and POME). They are used mainly in three different type of technologies; BTG, biorefinery, and anaerobic digestion. The most mature technology among the projects is BTG and the least mature one is anaerobic digestion (Fig. 36.9).

Cambodia

In Cambodia, gasification is the most popular technology found in our project database followed by carbonization.

Most of the projects are using rice husk as the feedstock. And while none of the project is in higher readiness level (Fig. 36.10), the ones operating in Tonle Sap and Kampong Cham state are already operating in very small capacity.

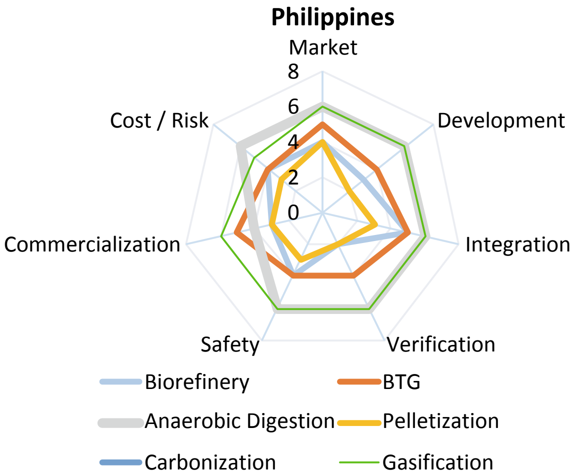


Fig. 36.8 TRL of Japan-supported biomass energy technology development projects in the Philippines

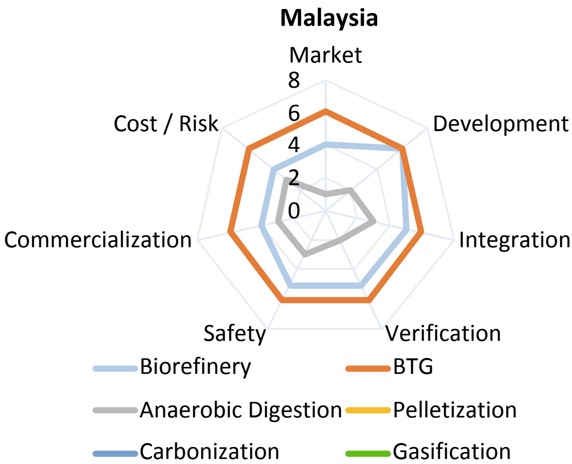


Fig. 36.9 TRL of Japan-supported biomass energy technology development projects in the Malaysia

Laos

There are only two projects in our database that are operating in Laos. One is an anaerobic digestion project operating in Champasak (GEC 2015a) using organic waste from tapioca factory as their feedstock. The other one is a direct combustion project operating in Vang Vieng (GEC 2015b) using rice husk as the feedstock. While both projects are already generating electricity and/or heat, they are not yet fully commercialized yet (Fig. 36.11).

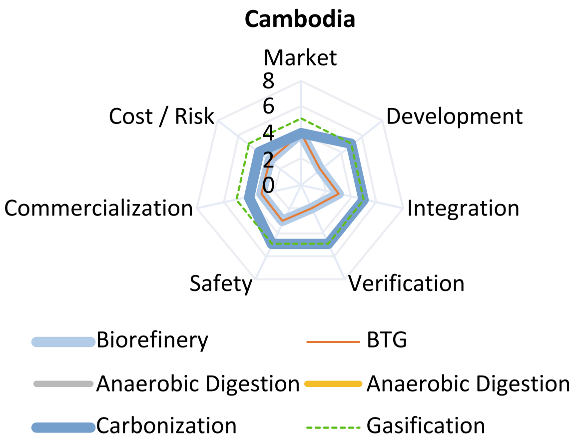


Fig. 36.10 TRL of Japan-supported biomass energy technology development projects in the Cambodia

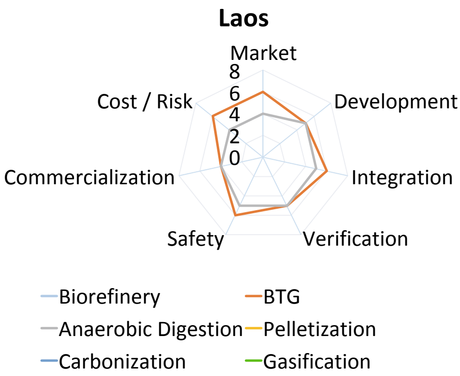


Fig. 36.11 TRL of Japan-supported biomass energy technology development projects in the Laos

36.4 Analysis and Discussions

36.4.1 Comparison of the Three Methods Results

To compare the results of technology readiness level measured using the three methodologies discussed in this study, the results distribution is compared by observing the shape of distribution curve from each method's results. The distribution curve from the results of each method is shown in Figs. 36.12, 36.13 and 36.14. Table 36.4 shows the descriptive statistics of the results of each method. Each of the distribution curve has the same mean and standard of deviation with the bar chart. Comparing distribution curves between the three methodologies results, could give us a quick visual comparison of how similar or different they are. It can be observed that the shape of distribution curve of Method 1 (the generic terminology

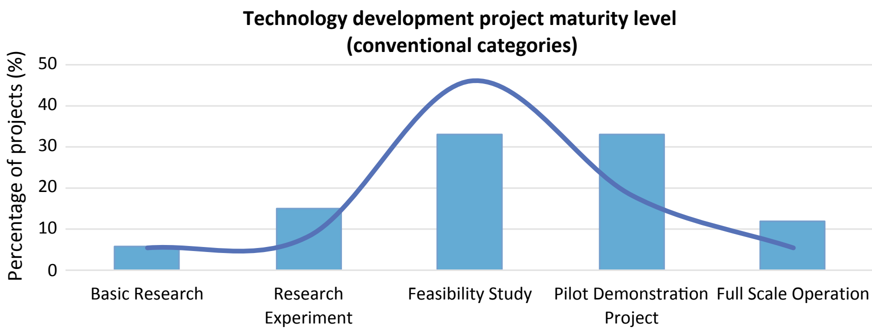


Fig. 36.12 Distribution curve of Method 1 results

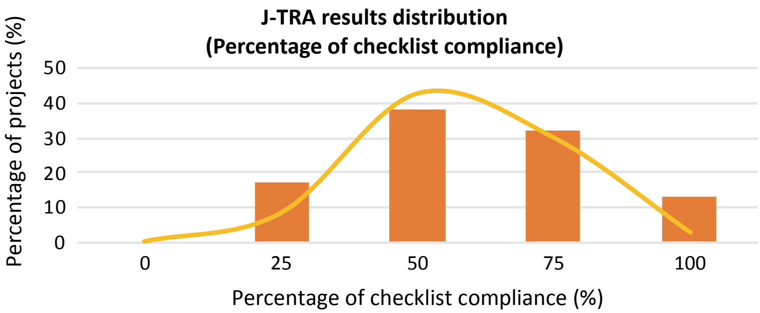


Fig. 36.13 Distribution curve of Method 2 results

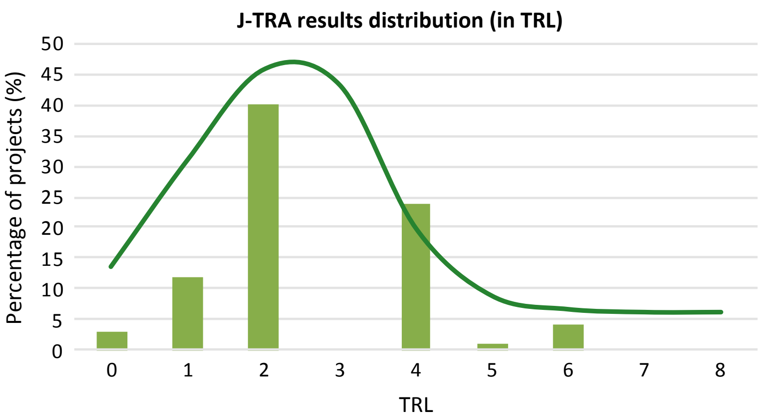


Fig. 36.14 Distribution curve of Method 3 results

Table 36.4 Descriptive statistics of each method

Method 1		Method 2		Method 3	
Mean	16.8	Mean	20	Mean	9.33333333
Standard Err	4.74763099	Standard Err	6.80441033	Standard Err	4.65772954
Median	13	Median	17	Median	3
SD	10.6160256	SD	15.2151241	SD	13.9731886
Kurtosis	−2.7638374	Kurtosis	−1.2780859	Kurtosis	2.17910606
Skewness	0.27774386	Skewness	−0.095818	Skewness	1.68419433
Count	5	Count	5	Count	9

of technology readiness levels) result and Method 2 (percentage of checklist compliance of the J-TRA parameters) result are similar. However, Method 3 (J-TRA results in TRL), while the curve looks very different from the previous two methods, it has positive skewness value, which is similar to Method 1. This imply that given the simplicity of Method 1, it is actually good enough to inform the overall progress of a project's readiness. The weakness of Method 1 is however, that it does not allow one to identify what aspect of the technology development that is preforming poorly (the bottleneck) and therefore it is difficult to, for example, determine budget priority in order to accelerate the project towards a higher readiness level.

36.4.2 The Common Bottleneck and Opportunities Among the Technology Development Projects

Among the discussed projects in different Southeast Asian countries (Sect. 3.3), the most prevalent challenges were the "commercialization" and "verification" aspects. The checklist questions of the commercialization element are around the issues of business development, mass production, and major issues for horizontal development. Indicating that most of the projects' bottleneck are not yet commercialized. Commercialization leads to cost reduction and ease for mass dissemination. On the other hand, the checklist questions of the verification element are around the issues of whether CO_2 reduction techniques have been considered and integrated to the developed technology and whether the technology work in the actual target environment. This indicates that some of the projects have not been measured for its CO_2 reduction effect and tested for an actual full-scale operation in the targeted environment.

36.5 Summary

There is a number of biomass energy conversion technology development project in the Southeast Asian countries under the support of Japan with its various mechanisms. A database containing information of these projects were constructed and analyzed to understand the readiness levels of these projects. There were three methodologies discussed in this project; Method 1: The generic terminology of technology readiness levels, Method 2: The percentage of checklist compliance of the J-TRA parameters, and Method 3: J-TRA results in TRL. Answering the research questions of this study, it can be concluded that; (1) While all three methodologies could present information about the general progress and readiness level of a project, Method 1 is easiest and quickest to do for identification of readiness level, (2) for a more detailed information about the bottleneck of a project, Method 3 is the most appropriate, and (3) While Method 1 and 2 present similar results about the status of progress in technology readiness, Method 3 is quite different especially with in terms of the distribution of results from a number of projects analyzed in this study.

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Chapter 37
Evaluation and Improvement Proposals for a Business Facility Solar and Ground-Heat Hybrid Heat Supply System

Daiki Yoshidome, Ryo Kikuchi, Andante Hadi Pandyaswargo, and Hiroshi Onoda

Abstract In this study, we proposed improvements based on actual measured data of a hybrid heat supply system that uses solar heat and ground heat as the heat sources of a restaurants complex in Honjo city, Saitama, Japan. Our evaluation from the actual monitoring measurements showed that the solar heat collection efficiency was 50–60%. The geothermal Heat Pump's Coefficient of Performance decreased significantly in the summer. We propose to set the heat insulation and burial depth of the piping from the ground heat collection to the heat pump and recommends five units of 5 units of solar heat collectors as the most ideal scenario.

Keywords Heat supply system · Solar heat · Ground heat · Hybrid heat supply system · Collaborative energy business · Energy efficiency

37.1 Introduction

In line with the adoption of the Paris Agreement, Japan has set a number of greenhouse gas reduction targets. For example, in the civil society sector, it has set a target of a 40% greenhouse gas reduction by fiscal 2030 with 2013 baseline. In the civil society sector, businesses accounts for more than 60% of emissions. This is because the demand for energy is increases as constructions of floor space increases. This is closely related to the use of air conditioners especially during severe winter seasons and intense heat in the summer season. Although renewable energy obtained from the sun is suitable for local production for local consumption, and various uses such as electric power, hot water supply, and air conditioning are mentioned, (Horiike and Nagano 2015; Maeta and Ozaki 2013; Herrando and Markides 2016; Hirata et al. 2016) there are challenges associated to such systems. For example, there are cases of system capacity excessiveness or insufficiency. These are caused by insufficient data recording and analysis. Such problems often lead to failure of system function.

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In this research, we analyzed a hybrid heat supply system using solar heat and ground heat used in the restaurants complex near Honjo Waseda station located in Honjo city, Saitama Prefecture. Our aim is to record data of the heat supply system, analyze it, and make an improvement proposal.

37.2 Heat Supply System Overview

37.2.1 Supply Area Overview

Figure 37.1 shows the city blocks targeted for heat supply by the solar heat and ground heat hybrid system. Store B and Store C in the map receives heat supply from the system (Zhao et al. 2018).

37.2.2 Supply System Overview

We installed meters on the pressure gauges, power meters, calorimeters, thermometers, and other equipments to record performance data in the heat supply piping. In addition, activities on the power switch control of the device is also recorded. By doing this, we were able to measure the activities as precise as units per one minute.

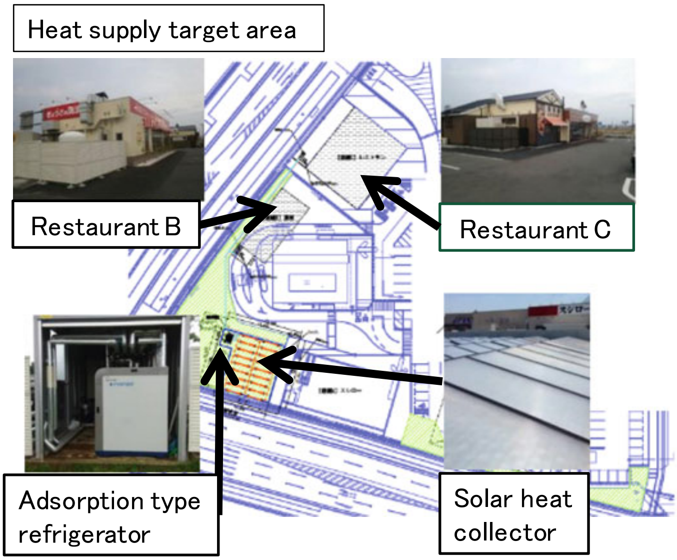


Fig. 37.1 Heat supply target area (Horiike and Nagano 2015)

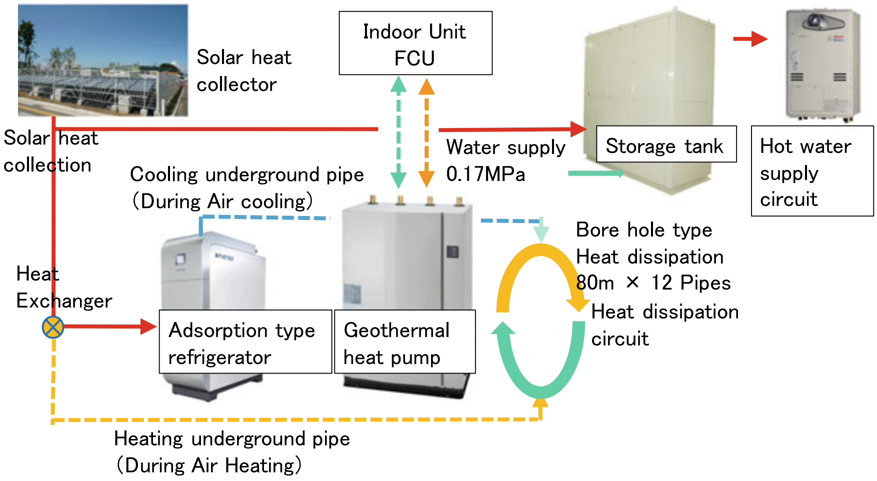


Fig. 37.2 System installation equipment (Horiike and Nagano 2015)

The system flow of the solar heat and ground heat hybrid system is shown in Fig. 37.2. In the summer seasons, it operates as a hybrid heat source by operating the adsorption type refrigerator that can operate at a low temperature using the acquired solar heat and supply the output to the geothermal heat extraction flow. In addition, in the winter seasons, heat is transferred directly to the underground piping to exchange heat from the sun, thereby warming the ground and using it as a hybrid heat source. Antifreeze technology is used for underground piping, and air conditioning is supplied to each of the stores using water-cooled heat pump. For hot water supply, the water in the storage tank is preheated by heat exchange using the antifreeze liquid warmed by a gas water heater powered with solar heat. A borehole type closed loop system is adopted for underground heat collection piping, and a total of 12 heat collection pipes are used. In addition, 16 solar heat collectors are installed, and the installation angle is 15°. Furthermore, the adsorption type refrigerator is conditioned to operate only in a time zone in which the pipe temperature of the solar heat collector reach 55 °C or higher. The specifications of each equipment are shown in the Table 37.1, Fig. 37.3.

Table 37.1 The equipment specifications

Facilities	Specification
Bore hole	80 m × 12 pipes
Solar heat collector	16 sheets = 190.4 m^2
Hot water supply	Solar heat, Gas water heater
Air conditioning equipment	Geothermal heat pump, Solar heat, Adsorption type refrigerator
Geothermal heat pump	30 kW × 4
Storage tank	1500 L × 3
Adsorption type refrigerator	10 kW

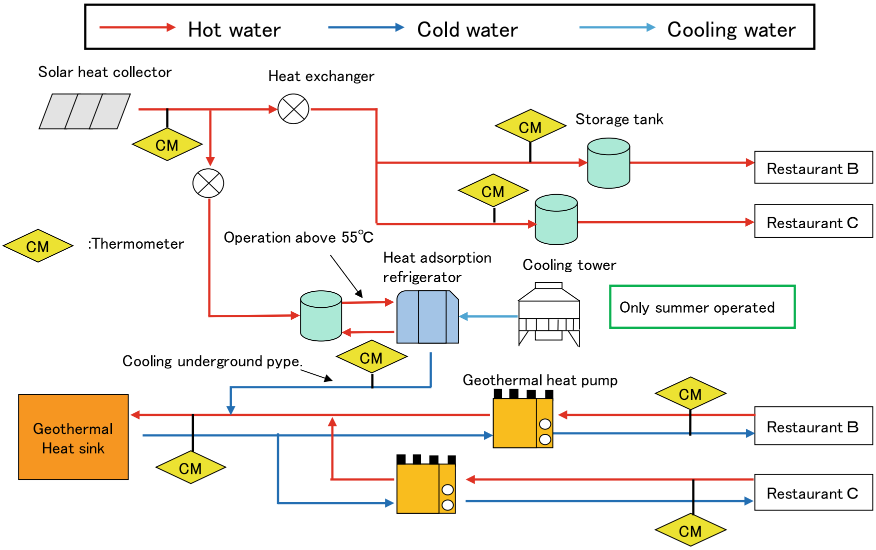
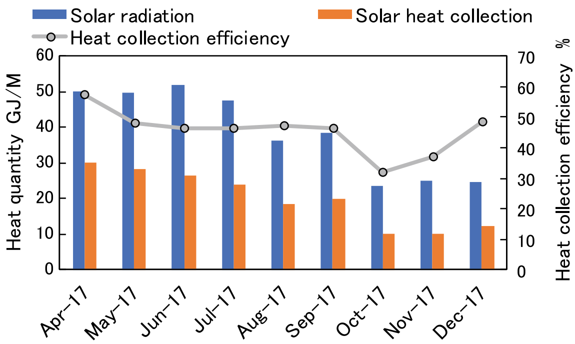


Fig. 37.3 The flow of heat supply system

Fig. 37.4 Heat collection efficiency



37.3 Actual Measured Evaluation and Analysis of Heat Supply System

37.3.1 Performance Evaluation of a Solar Thermal Collector

In Fig. 37.4, we show the solar heat collection amount and the collection efficiency by month. The formula to calculate heat collection efficiency is shown by Eq. 37.1. The amount of solar heat collection depends on the amount of solar radiation, and the collection efficiency is generally stable throughout the year. On the other hand, we found that in the summer season when the heat collection amount reached its maximum, the heat supply amount became excessive, and eight panels out of 16 had to adjust the heat collection amount. From these data, it can be confirmed that there is a gap between the heat demand and the supply amount.

$$\eta_k = \frac{Q_k}{Q_s} \tag{37.1}$$

η_k: Heat collection Efficiency [%]
Q_k: Solar heat Collection [MJ]
Q_s: Solar radiation [MJ]

37.3.2 Performance Evaluation of Adsorption Type Refrigerator

The formula used to calculate the energy utilization rate is shown in Eq. 37.2 and Fig. 37.4 show the Coefficient of Performance (COP). The cold energy output of the adsorption type refrigerator are shown by month. In addition, the calculation method of COP (=0.6) was shown Fig. 37.5. We found that the output of the adsorption type

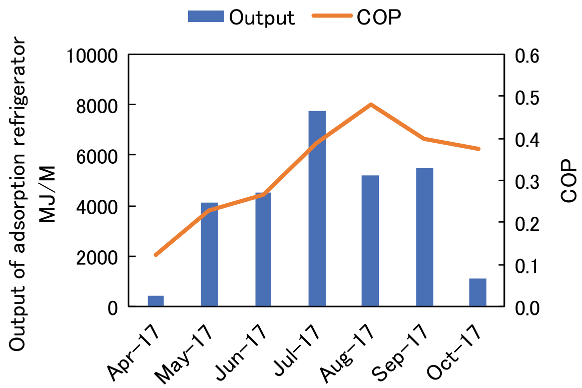


Fig. 37.5 Energy output and COP

refrigerator is dependent on the outside air temperature, as it is the highest in July when the average outside air temperature is high. This was not the case in May where the heat collection is the highest. In addition, COP tends to decrease in months when output is small, and there is no month that satisfies rated COP = 0.6. It has been found that the COP of the adsorption refrigerator increases as the temperature of the low-temperature heat source increases. It is thought that the reason why the COP is lower as the outside air temperature is lower is because the antifreeze temperature after solar heat collection is lower.

37.3.3 *Performance Evaluation of Adsorption Type Refrigerator*

The geothermal heat pump is installed in a section close to each store, and the ground heat collecting pipe to the heat pump are connected by underground piping. The chart below shows the air conditioning load, power consumption, and COP is shown by month. Compared to COPs in the middle and winter seasons, both stores have less than half the COP in summer, indicating that they have not reached the rated COP. In addition, in the store B, the COP from October to December was less than a half of the store C. This might indicate that the power consumption had been increased for some reason (Fig. 37.6). One possibility is that the store's air conditioning setting is affecting this factor. We plan for an interview survey to confirm about this.

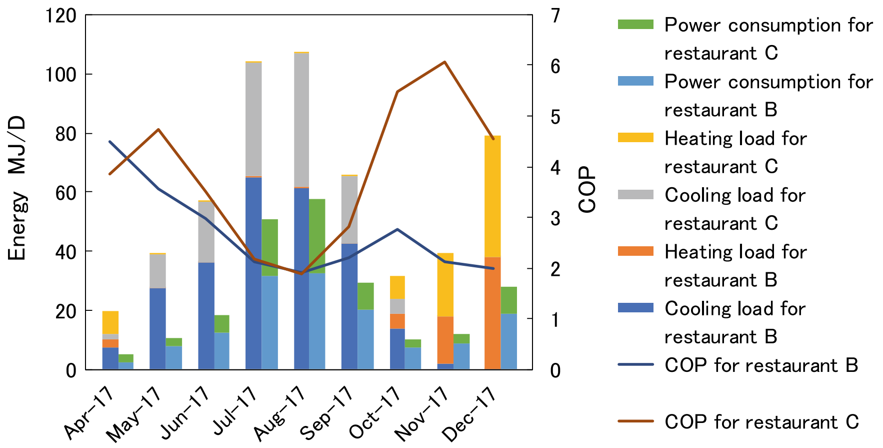


Fig. 37.6 Air conditioning load, power consumption of geothemal heat pump and COP

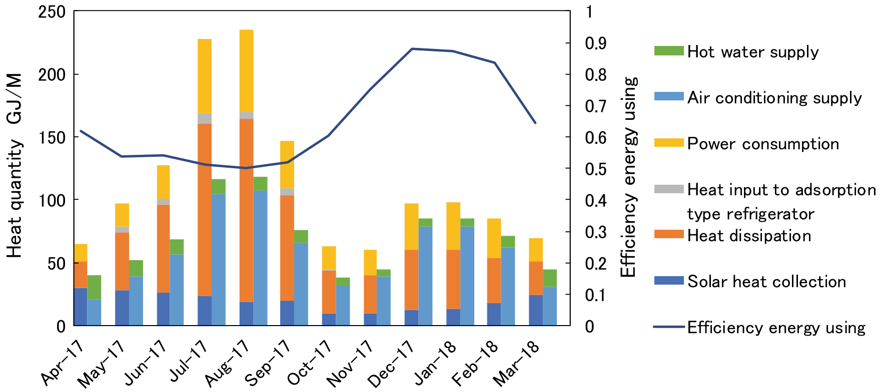


Fig. 37.7 Energy utilization rate of each energy and the whole system

37.3.4 Performance Evaluation of the Entire System

In Fig. 37.7 we show the calculation method of the energy utilization rate and we present the energy utilization rate of the whole system by month. The formula for calculating energy efficiency is shown in Eq. 37.2. The result showed that the energy utilization factor in summer is low, and it can be observed that the amount of heat extraction from the ground heat is largest. This is considered to be due to the decrease in the COP of the geothermal heat pump in addition to the increase in the power consumption.

$$E = \frac{P}{P_c + Q} \tag{37.2}$$

E: Energy utilization rate [%]
P: Output [MJ]
$\boldsymbol{Pc}$: Power consumption [MJ]
$\boldsymbol{Q}$: Heat input [MJ]

37.4 System Improvement Proposal

37.4.1 Factor Analysis of Air Conditioning Malfunction of Store C

In the summer of 2018, the air conditioning system malfunctioned in store C. Furthermore, the store's thermal environment could not be maintained. At the same time, the temperature in Honjo City at that time has exceeded 40 °C. The geothermal

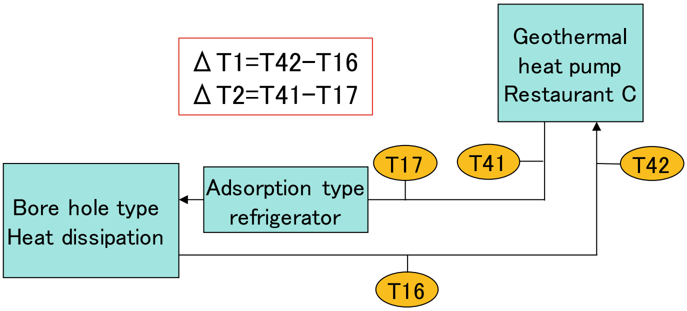


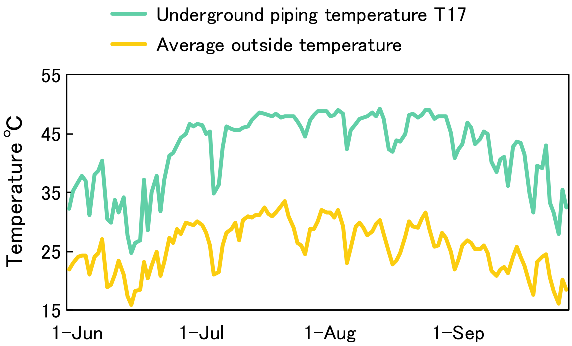
Fig. 37.8 The system flow including the geothermal heat pump

heat pump was down due to intense heat. Triggered by this situation, we analyzed the system including the geothermal heat pump of the store C and performed the factor analysis of the air conditioning malfunction. The system flow including the geothermal heat pump is shown in Fig. 37.8.

First, we investigated the operation condition of geothermal heat pump when air conditioning failure occurred. Normally, when the refrigerant temperature on the heat radiation side rises, the COP of the Heat Pump (HP) decreases. Therefore, we analyzed the inlet temperature (T42) of the geothermal heat pump in summer. We found out that there were many days where the temperature exceeded 50 °C occurred in summer. This has caused the fall of COP (Figs. 37.9, 37.10).

Another possible cause of the temperature rise of T42 was that the heat medium which moves within piping is receiving the influence of surface temperature. As such, when we analyzed the values of ΔT1 and ΔT2 in summer, in 2018 when the outside air temperature was high, ΔT1 was 7 °C and ΔT2 was close to 5 °C, and we noticed they were greatly affected by the surface temperature (Fig. 37.11). At present, underground piping is not heat-insulated, and the depth of the piping is not sufficient. With this situation, heat loss will occur. We proposed that it is necessary to provide a heat insulation around the piping and to install underground piping in sufficient depth.

Fig. 37.9 Underground piping temperature and average outside temperature



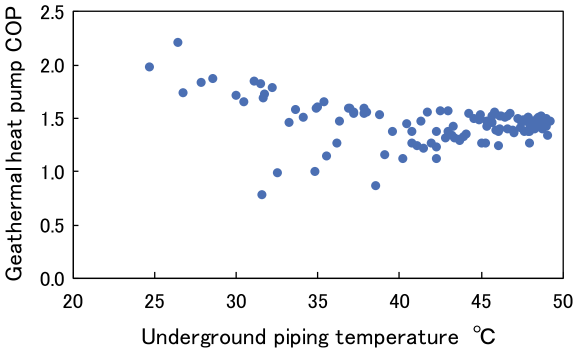


Fig. 37.10 Underground piping temperature and geothermal heat pump COP

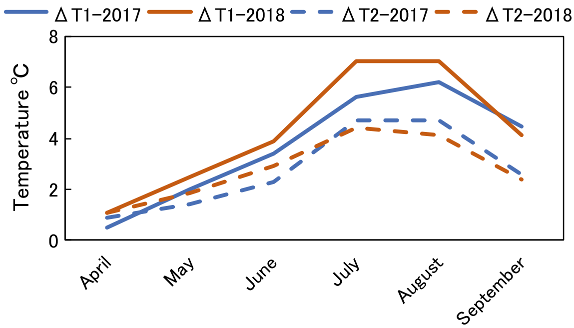


Fig. 37.11 Temperature of ΔT1 and ΔT2 in 2017 and 2018

We also found that a gap is generated between the cold heat supply by the geothermal heat pump and the heat demand of the store C. After we analyzed the cooling load of the store C. we found that when the average outside temperature exceeded 30 °C, the cooling load of the store C exceeded the capacity of the geothermal heat pump, and unable to supply enough cold heat during the store operating time zone in summer (Fig. 37.12).

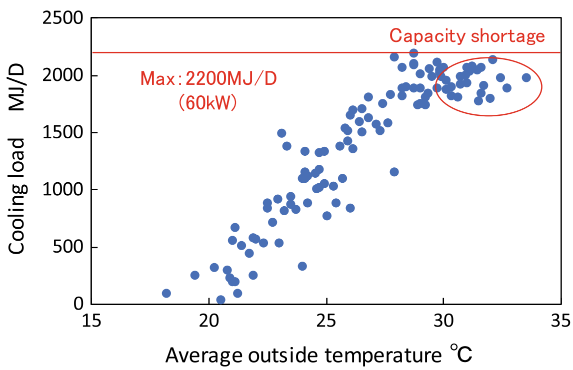


Fig. 37.12 Capacity shortage of geothermal heat pump

We plotted the correlation between the average outside air temperature and the cooling load (Fig. 37.12). The required capacity of the ground heat pump was calculated by linear approximation. Then, it turned out that the geothermal heat pump needs the capacity of 75 kW. Also, due to the fact that similar problems did not occur in store B, the required cooling capacity is lower than store C because store B has relatively few windows and has high insulation performance due to the structure of the building. As a countermeasure against air conditioning malfunction, Store C added an air conditioner with an air heat source, resulting in a significant increase in costs.

37.4.2 *Operation Analysis of the Absorption Refrigerator*

The adsorption type refrigerator operates under constant summer conditions and uses the low temperature heat source obtained from the solar heat collector to supply cold heat into the system of geothermal heat pump. The system flow is shown in the Fig. 37.13.

Here, we organized the ΔT3 and ΔT4 at the working day of the refrigerator. Then, we found that endothermic was performed about 1 to 3 degrees on the working day (Fig. 37.14). Moreover, we confirmed that when the outside air temperature is higher the output of the refrigerator also increased. It is considered that this is because the higher the heat source temperature of the adsorption type refrigerator, the higher the COP.

Fig. 37.13 The system flow of adsorption type refrigerator supply

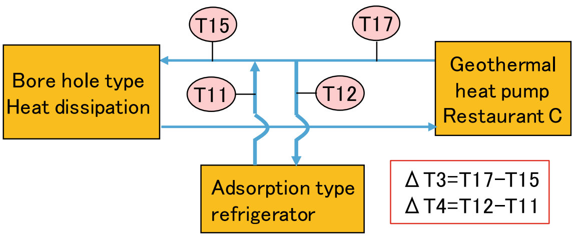


Fig. 37.14 Average outside temperature and ΔT3 and ΔT4

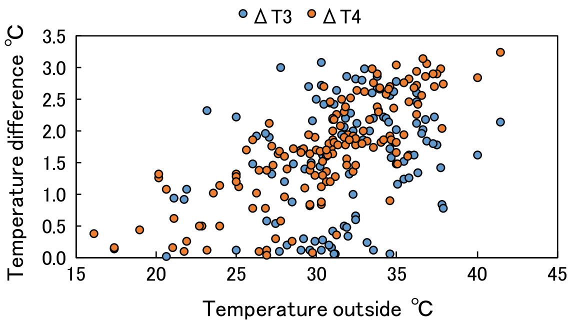


Table 37.2 Ratio of refrigerator to total output

Month	Heat dissipation	Output of adsorption type refrigerator	Ratio of refrigerator to total output
	MJ/M	MJ/M	%
April	20,790	460	2.21
May	46,390	4150	8.95
June	69,800	4530	6.49
July	137,250	7760	5.65
August	145,810	5190	3.56
September	83,720	5490	6.56

In Table 37.2, we compared the Geothermal-heat heat collecting amount and the Output of adsorption type refrigerator. It can be observed that the ratio is less than 10% in many months. This finding proves that the influence of adsorption type refrigerator is not so critical. The capacity of the adsorption refrigeration machine is the smallest unit due to the installation area and cost, but it is effective to increase the capacity considering that the amount of solar heat collection is surplus in summer.

37.4.3 Operation Analysis of a Solar Energy Absorber

It has been observed from the energy utilization rate of the entire system, that the amount of solar heat collection in summer is excessive. Therefore, we organized how the heat collection amount fluctuates by changing the number and angle of solar heat collectors. Equations 37.3 and 37.4, a formula for estimating the amount of heat of solar heat is shown. From the above calculation formula, we understand that when we increase the solar heat collector's angle, the heat collection amount of the solar heat collection increases in winter and decreases in summer. Therefore, it is considered effective to change the installation angle of the solar heat collector according to the demand forecast.

$$Q_h = Q_{sp} \times \frac{\sin(h+\theta_v)}{\sin(h+\theta_a)} (h + \theta_a < 90^\circ) \tag{37.3}$$

$$\boldsymbol{Q_h} = \boldsymbol{Q_{sp}} \times \left(1 - \frac{\sin(\boldsymbol{h}+\boldsymbol{\theta_v} - 90^\circ)}{\sin(\boldsymbol{h}+\boldsymbol{\theta_a})}\right) (\boldsymbol{h} + \boldsymbol{\theta_a} \geq 90^\circ) \tag{37.4}$$

$\boldsymbol{Q_h}$: Virtual heat collection [MJ]
$\boldsymbol{h}$: Solar altitude [°]
$\boldsymbol{\theta_a}$: Actual installation angle [15°]
$\boldsymbol{Q_{sp}}$: Solar heat collection [MJ]
$\boldsymbol{\theta_v}$: Virtual installation angle [°]

37.4.4 Proposal for Improvement of the Whole System

From the present situation where the effect of adsorption type refrigerator is ineffective and solar heat collection amount is excessive, we would like to propose an improvement measure for the system (Figs. 37.15, 37.16). We presented the changes in the amount of heat collected and heat demand changes as the number and angle of panels of the solar thermal collector were changed. Currently, it is necessary to secure the amount of solar heat collection during the summer because the adsorption chiller is in operation. On the other hand, considering the impact of leased land costs and fluctuations in the number of heat collectors , it is better to stop and remove the

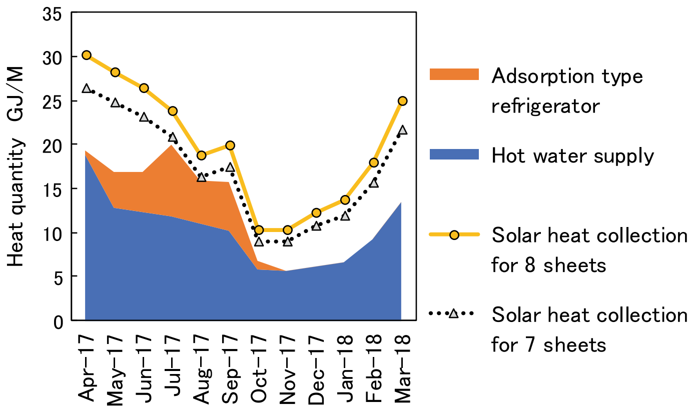


Fig. 37.15 Number of solar thermal collectors with adsorption type refrigerator

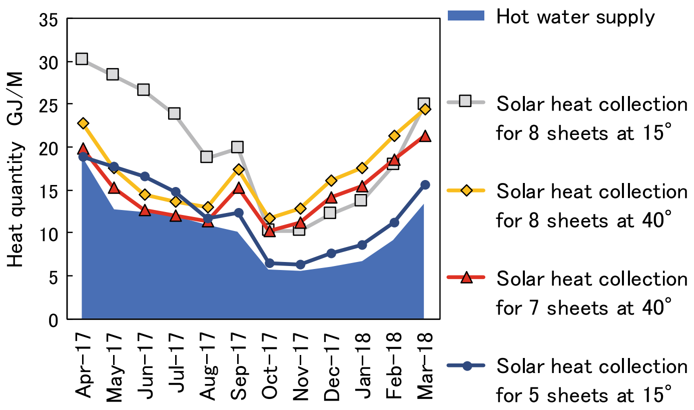


Fig. 37.16 Number of solar thermal collectors when the adsorption type refrigerator is removed

adsorption chiller, and as a result, the number of heat collectors can be reduced to five. In addition, as for the angle, as a result of considering heat collection in the intermediate period and safety aspects, it will be maintained at the current angle without changing from 15°.

37.5 Discussions

37.5.1 Solar Heat Collector Working Procedure

Solar heat is generally used for air conditioning in the winter time and as hot water supply throughout the year. According to a NEDO survey, solar heat utiliziation is mainly for hot water supply (78%), and room heating (43%) (Agency for Natural Resources and Energy 2019a, b, c) In addition, the solar heat collectors are considered more effective for these purposes because they have a higher energy utilization efficiency (50–60%) compared to the power generation efficiency of solar power generation. The down side of solar heat collector is that heat can only be transported in limited ways compared to electricity. In the hybrid system discussed in this study, the surplus solar heat could not be consumed by the adsorption refrigerator, and as a result, half of the solar heat collectors have stopped working. Moreover, since solar heat is an unstable supply, it is necessary to put in a separate hot water supply system as a backup. It should not be expected that solar heat will cover the whole amount of heat demand. Therefore, in order to improve the energy utilization rate of the system, it is important to supply only the amount that can be used as the capacity of the solar heat collector. The energy utilization rate when the solar collector is set to 5 and the adsorption refrigerator is removed is shown in Fig. 37.19. In the calculation, the heat collection amount before the change is assumed to be 16 sheets. As for heat loss and pressure loss in the piping, it was assumed that there are about 30% of loss in the winter time. The annual heat use had decreased by 2.5%, but the average energy utilization rate had improved by 15%. In addition, because the installation area of the solar heat collector and adsorption chiller can be reduced (11 solar heat collectors × 11.9 m^2 plus adsorption chiller approximately 1 square), there was about 131.9 m^2 reduction. According to the 2016 heat supply business manual (Japan Heat Supply Business Association 2016), the unit price of heat supply is 7.01 yen/MJ in the Kanto region, and the revenue decreases by 149,374 yen per year due to the decrease in hot water supply. Furthermore, as the site rent of 131.9 m^2 can be reduced, 2.4 million yen can be saved. From the viewpoint of cost evaluation, it was found that it would be more cost effective to set the capacity precisely in order to avoid heat collection surplus rather than to have it at its maximum capacity (Figs. 37.17, 37.18).

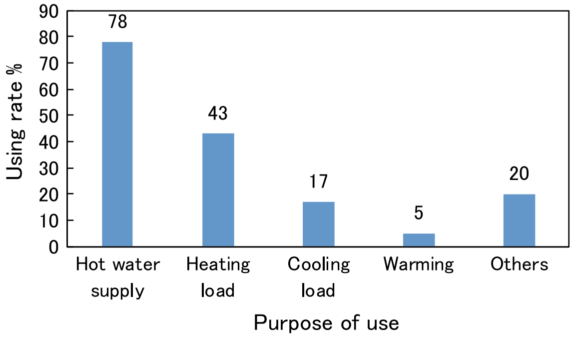


Fig. 37.17 Purpose of using solar heat energy

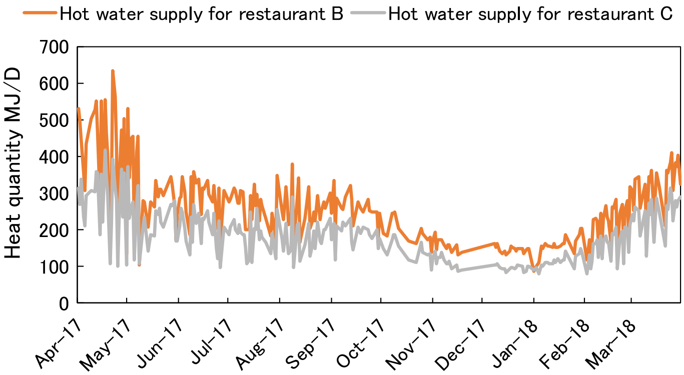


Fig. 37.18 Hot water supply per day for two restaurants

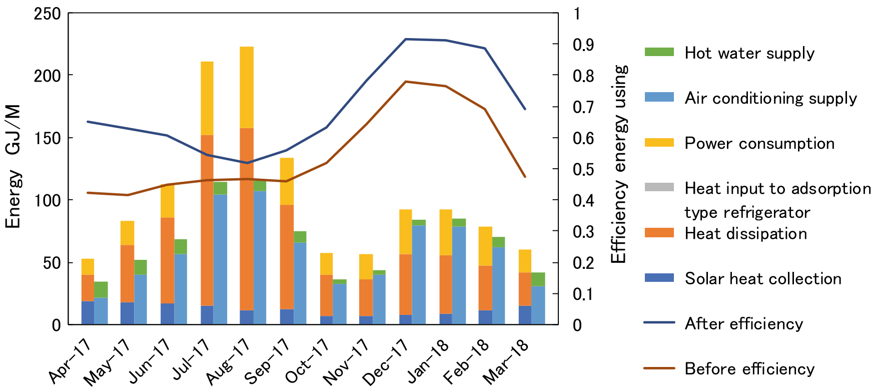


Fig. 37.19 Changes in energy use efficiency

37.5.2 Geothermal Heat Pump Working Procedure

In the project discussed in this study, the capacity of geothermal HP was insufficient and air conditioning problem occurred at store C. The use of a solar heat collector was backed up by a hot water heater, but the air conditioning was entirely covered by underground heat HP. The cost of retrofitting had greatly increased due to insufficient capacity. To avoid such occurence, it is necessary to set a capacity exceeding the predicted maximum load in the geothermal HP. This is in contrary to the example of the solar heat collector. As mentioned earlier in Sect. 37.4.1, the geothermal HP capacity had to be set to 75 kW. Furthermore, in addition to a simple calculation of the total floor area, it is necessary to clarify the main load factors of the store and consider the heat insulation performance of the building for capacity setting. It is necessary to grasp the above points in advance, but in the modern days there are many cases where land infrasctuctures are developed at a stage where tenants have not come to decide on how to use the buildings. In order to make effective use of renewable energy heat, it is necessary to set capacity systematically at the stage of land infrastructure development, and to design it together with a tenant who will use the facilities.

37.5.3 Utilization of Solar/Geothermal Hybrid System

In this project, it was worth noting that solar heat and underground heat were used as a hybrid system, but as a result, the hybrid system did not work well, resulting in a lack of capacity and surplus. As described above, the most important point in solving this problem is that it is most effective to improve the accuracy of demand prediction by organizing or setting tenant information to some extent at the stage of land preparation. For example, if the load demanded by the tenant is known in advance and the capacity is set properly, the installation cost of underground piping will be reduced, the rise in the piping temperature of the underground thermal HP will be eliminated, and the solar heat collector usage area will be reduced. It is clear that by doing these steps unpredicted high costs can be avoided. Furthermore, since the occurrence of air conditioning malfunctions and the cost of adding air conditioners can be reduced for the demand side, it is considered that the tenant information in advance is beneficial to both parties.

37.6 Summary

The following findings were obtained by data analysis of the solar heat/ground heat hybrid heat supply system in the commercial facilities:

- The amount of heat from solar heat depends on the amount of solar radiation, and the heat collection efficiency is stable at around 50%.
- We confirmed that the COP of the adsorption type refrigerator using solar heat does not meet the rated COP = 0.6, and the efficiency decreases when the outside air temperature becomes lower.
- The geothermal heat pump of store C in summer is about COP = 2 which is about a half of the COP in winter. The COP of the heat pump of store B is always at a low level throughout the year.
- The energy utilization rate of the entire system is the lowest in summer at about 50%. This was caused by the increase in power consumption and the decrease in COP of the geothermal heat pump.
- We confirmed that the air conditioning malfunction at store C in fiscal year 2018 was caused by the increase in the temperature at the entrance to ground heat pump and the shortage of capacity of ground heat pump. In addition, as the factor that the entrance temperature of the geothermal heat pump rises, the heat insulation of the piping was not enough. The temperature rise between the ground heat pump and ground heat sampling tube was 12 °C.
- The piping temperature in summer is reduced by 2 °C as a result of cold supply by an adsorption type refrigerator. On the other hand, it was confirmed that the amount of output of adsorption type refrigerator was about 2–10% compared to the heat extraction amount.
- We were able to match the heat supply with the heat demand when we adjusted the angle of solar heat collectors to 15° and reduced them to only 5 units.

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Chapter 38
The Import Structure of LNG from Russia to Japan by Cognitive Map and Text Analysis

Kengo Takeda, Norovsambuu Purevsuren, Koji Tokimatsu, Masako Ikegami, and Mikael Hook

Abstract Japanese energy policy was shifted to natural gas use due to drastic situation domestic and international energy situation, such as the Fukushima Daiichi nuclear accident. Accordingly, this study analyzes the structure of natural gas development project and trading between Japan and Russia, as Russia is increasingly becoming an important major supplier of natural gas, which is reflected in the bilateral trade. This study will analyze the two LNG projects as a representative case of the multinational development project of natural gas from the perspective of energy security, economy, technology, and politics. The method of this analysis is "cognitive map" and "text analysis" to quantify the qualitative data collected from four major Japanese newspapers during the period of 1991-2017. One of the findings of this study is that, the Russian government has strengthened exporting LNG to East Asia as a state project since the first Putin administration especially after the US Shale revolution and the Ukrainian crisis, while the Japanese side is driven by major private corporations such as the construction of infrastructure which is little affected from international politics.

Keywords Energy policy · LNG import · Russia · Japan · LNG projects

38.1 Introduction

In Japan's energy policy, the importance of natural gas is considered important and expected to remain unchanged. In Japan, the introduction of renewable energy will be halted due to difficulties in securing safety and resuming operation of nuclear power plants after the Fukushima Daiichi Nuclear Power Plant accident, changes in power transmission networks and fixed price purchasing systems, and so on. On the

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other hand, the dependence on fossil fuel energy, which has risen since the shutdown of nuclear power plants, is expected to increase. The proportion of thermal power generation, which was 65% in 2010, will be 83% in 2016 (AERE 2015; Ishii 2008).

Japanese oil import is hugely dependent from the Middle East where geopolitical risks are high due to instability in the region. Also, Japanese domestic demand and demand from neighboring countries, South East Asian countries, are rising. Japan is one of the important destinations for Russia which has close geographical distance. Therefore, it is possible to obtain the suggestion of the stable gas import for Japan by the case analysis of the past gas import from Russia where import volume of Japan is expected to increase in the future. Therefore, in order for Japan to take lower risk policy decisions in the natural gas import business from Russia, we will clarify causal factors and the factors that have been influenced by past case analysis of Russian natural gas exports.

In this study, we conducted case studies on the Yamal LNG Project and the Sakhalin 2 Project. The Yamal LNG Project is a gas development project on the Yamal peninsula in the northern part of the Yamal-Nenets Autonomous Region on the Russian West Siberian Arctic coast, and its interest is broken down as of 2018 by Novatek, Russia's private natural gas, and hydrocarbon integrated company. 50.1, 20% of total French-based international oil capital, 20% of CNPC (China National Petroleum Corporation), and 9.9% of the Chinese government's Silk Road Foundation. The estimated reserves are 698 BCM (billion cubic meters) of natural gas and 120 million BBL (barrel) of condensate, and exports by three LNG baselines with a capacity of 5.5 million tons are planned.

The Sakhalin 2 Project is an oil and natural gas development project in the Piltun-Astokhskoye Block and the Lansky Block on the east coast of Sakhalin Island in the Far East of Russia. And the share of the interests of Sakhalin Energy Co., Ltd. Gazprom, the largest integrated natural gas company, has 50% + 1 share, Royal Dutch Shell of international oil capital has 27.5% − 1 share, Mitsui & Co. has 12.5%, and Mitsubishi Corporation has a 10% stake. The estimated reserves are about 750 billion BBL for crude oil and about 500 BCM for natural gas.

Common points in these two projects include the fact that Japan supports export in the form of LNG currently established as a natural gas import system, and that Japanese companies are participating in the plant construction process of each project, etc. As of 2017, Japan imported at least 7.27 million tons of LNG, 8.7% of the total, from the Yamal LNG Project with a long-term contract. The diversification of suppliers and the development of the Arctic Ocean route are expected to increase imports of the Yamal LNG Project and gas from the region. As for research questions, we will focus on two points: the turning point of Russia's natural gas export strategy and the pros and cons of possessing Japanese interests in terms of energy security in development projects in Russia.

38.2 Qualitative Analysis: Cognitive Map

38.2.1 Methodology

The software "KH Coder" (Higuchi 2014, KH Coder) used in this study was developed by Associate Professor Koichi Higuchi of Ritsumeikan University and is free software that has published all the processing contents since 2001. As of 2018, this software has been used in more than 2000 research cases, and the fields range from policy evaluation, media analysis, and verification of educational effects.

Among the functions provided in KH Coder, the following functions were used in each process in this study.

- Process (1): "extraction word list" "extraction word: hierarchical cluster analysis"
- Process (2): "extraction word: co-occurrence network" "coding: cross tabulation"

Using a database of four major newspaper companies (Nikkei, Yomiuri, Asahi, and Mainichi) as information sources (Nikkei Telecon, Yomidas Rekishikan, Kikuzo II Visual, Maisaku), we will extract important terms by text analysis and create a "cognitive structure map" (Yamamoto and Tani 1979) based on that. It is possible to extract highly relevant related factors in each period.

38.2.2 Setting Period

In the process of qualitative analysis (1), "cognitive structure diagram" was created using the functions "extracted word list" and "extracted word: hierarchical cluster analysis" of KH Coder.

We extracted words that show remarkable appearance throughout the text, and words that show correlations between events and events of each policy trend such as "promotion," "growth," "interference," and "deterioration" that are essential for creating cognitive structure maps. In the process of collecting information, words such as "Russia" and "Natural gas" are automatically extracted in large numbers, so we chose not to disturb the analysis.

The function "extraction word: hierarchical cluster analysis" is to output combinations of similar words and phrases of appearance patterns in the form of dendrograms. Analyze all the articles, grasp the features of the appearance pattern for each frequent phrase, and automatically connect the words with similar appearance patterns with closer branches. It is possible to trace the dendrograms back together and group them together with words connected by close branches as factors that have influenced the policy. Hereinafter, it is called a related factor.

These factors are then organized into a matrix of this information. At this time, related factors affecting other related factors are placed in the leftmost column of the matrix, and related factors affected in the top row of the matrix. After that, based on the words "promotion" and "prevent" in the sentence, the relationship between related factors is based on the words “promotion” and “interference”, and if the correlation is positive, then “+1” or negative Enter “−1” for correlation, and enter “0” if there is no correlation (Yamamoto and Tani 1979; Urano 1997; Yakushiji 1989).

For the Yamal LNG Project, the period was set as follows. In Russia, the end date of the term and the arrival date of the new president will be the same day, but the term of the new president will start from the day after the arrival date to classify articles based on the date. The second Putin administration has more articles than the other administrations, so it was divided into two parts, the first and the second, and five periods were set as shown below.

- Period (1-1): The Yeltsin government, July 10, 1991-December 31, 1999
- Period (1-2): The first Putin administration, January 1, 2000-May 7, 2008
- Period (1-3): Medvedev administration, May 8, 2008-May 7, 2012
- Period (1-4): The second Putin administration first semester, May 8, 2012-May 7, 2014
- Period (1-5): Second Putin administration late, May 8, 2014-December 31, 2017.

For the Sakhalin 2 Project, the period was set as follows. Since the first Putin administration has more articles than other administrations, it was divided into three parts; first, middle, and second quarters. The boundary points between period (2-2) and period (2-3) are classified before and after the Natural Resources Supervision Bureau of Russia filed a lawsuit for suspension of construction on September 5, 2006. In addition, with regard to the boundary point between period (2-3) and period (2-4), it is the first report in an article dated December 22, 2006, that an agreement has been reached for Gazprom’s entry into the Sakhalin 2 project. As it became clear, classification was performed before and after that. From the above viewpoints, five periods were set as shown below.

- Period (2-1): The Yeltsin administration, July 10, 1991-December 31, 1999
- Period (2-2): First Putin administration first semester, January 1, 2000-August 27, 2006
- Period (2-3): The first Putin administration, August 28, 2006-December 21, 2006
- Period (2-4): The first Putin administration late, December 22, 2006-May 7, 2008
- Period (2-5): Medvedev, 2nd Putin administration, May 8, 2008-December 31, 2017 (Fig. 38.1).

38.2.3 Result (Sakhalin-2 LNG Project)

From the information in Table 38.1, the following can be interpreted as features of each period.

- Period (2-1): Backward base of Hokkaido (2-1-3, 2-1-7)/Development of foreign investment entry environment (2-1-8, 2-1-9, 2-1-10, 2-1-11)

Factors ＼ Results	JBIC：financing for Sakhalin 2	Sakhalin 2	oil spill accident in Sakhalin 2	sealing for Sakhalin 2	financing for Sakhalin 2	Sakhalin Projects	development in Sakhalin	development in Siberia	foreign capitalization	development in Far East Area	state government: integrated infrastructure	limitation for terms of producing
JBIC：financing for Sakhalin 2		1		1								
Asia Energy Community initiative								1		1		
gas long term contract		-1				-1						
environment of Sakhalin		-1										1
Sakhalin 2	1											
PS contract of Sakhalin 2								1	1			
provisional sealing Sakhalin 2				1								
sealing for Sakhalin 2											1	
Sakhalin Projects											1	
additional attending for Sakhalin												
Hashimoto Yeltsin Plan				1	1		1					
declining oil price		-1										1

Fig. 38.1 Cognitive map: period (2-1) (Partially shown)

- Period (2-2): Expense expansion of Sakhalin 2 (2-2-2, 2-2-10)/Large-scale customer contract (2-2-3, 2-2-11)/Environmental consideration in Russia 2-2-4)/Russia Resources State Control (2-2-5, 2-2-7)
- Period (2-3): Negotiation of interests (2-3-2, 2-3-6)/Environmental negotiations (2-3-4, 2-3-5, 2-3-8, 2-3 -11)/External stagnation factor (2-3-3)
- Period (2-4): Strengthening Japan-Russia energy cooperation (2-4-5, 2-4-8, 2-4-9)/Europe-US relations deterioration (2-4-6, 2-4-7, 2-4-12)/Strengthening Japan-Russia relations (2-4-10, 2-4-11)
- Period (2-5): Russia-Russia Strengthening Asia (2-5-2, 2-5-6)/Japan-Russia Summit Meeting (2-5-3)/New Gas Field Development (2-5-8, 2-5-9)

38.2.4 Result (Yamal LNG Project)

Cognitive structure The leftmost column of the figure is the related factor of the cause, the upper row of the figure is the related factor of the affected result, and the positive one is “+1” in the cell The value of O is used to place the cell in blue, and

Table 38.1 High-level concept Cognitive structure diagram "Sakhalin 2 project" (Partially shown)

No.	Term	Related factor	Frequency
2-1-1	term(2-1-1)	Sakhalin 2	37
2-1-2	term(2-1-2)	Sealing Sakhalin 2	14
2-1-3	term(2-1-3)	Change Hokkaido into a rear	9
2-1-4	term(2-1-4)	Oil spill accident in Sakhalin	7
2-1-5	term(2-1-5)	Sakhalin project	6
2-1-6	term(2-1-6)	JBIC: financing for Sakhalin	5
2-1-7	term(2-1-7)	Environment of Sakhalin	5
2-1-8	term(2-1-8)	Foreign capitalization	5
2-1-9	term(2-1-9)	Hashimoto and Yelstin plan	5
2-1-10	term(2-1-10)	RUS: legislation	5
2-1-11	term(2-1-11)	RUS: Lack of legislation	5
2-2-1	term(2-2-1)	Sakhalin 2	36
2-2-2	term(2-2-2)	Increasing operating cost	12
2-2-3	term(2-2-3)	Tokyo gas: purchase Sakhalin	8
2-2-4	term(2-2-4)	Environmental assessment	7
2-2-5	term(2-2-5)	RUS: nationalize natural	7
2-2-6	term(2-2-6)	JPN: diversify resource root	6
2-2-7	term(2-2-7)	Gazprom: attending negotiation	5
2-2-8	term(2-2-8)	Environment of Skhalin	5
2-2-9	term(2-2-9)	Sakhalin project	5
2-2-10	term(2-2-10)	Increase oil price	5
2-2-11	term(2-2-11)	Chubu power: purchase Sakhalin	5

the one in which the relationship is negative is placed in the cell with a value of "−1" and the cell is made red (Fig. 38.2).

From the information in Table 38.1, the following can be interpreted as features of each period.

- Period (1-1): Attention to Asian exports (1-1-3, 1-1-4, 1-1-6)/Beijing route pipeline construction (1-1-1)
- Period (1-2): Conflict with former Soviet Union countries (1-2-2, 1-2-9)/Japan-Russian-China relationship (1-2-3, 1-2-6, 1-2 -7, 1-2-8)/Beijing route pipeline construction (1-2-1)
- Period (1-3): Gazprom financial deterioration (1-3-4)/Maintenance of European supply capacity (1-3-7)/Full-scale start of Yamal development (1-3-1, 1-3-2, 1-3-3, 1-3-5)
- Period (1-4): Aftermath of Shale Revolution (1-4-2)/Transition to Asian Policy (1-4-1, 1-4-3, 1-4-4, 1-4-, 1-4-6, 1-4-7, 1-4-8)

Factors ＼ Results	Gazprom： development gas field in Iran	Gazprom： obtaining interest of gas field in Fa	Gazprom： earing capital	Gazprom： obtaining interest of gas filed in Ea	development gas field in Irkutsk	Yeltsin visit China	construction South Stream gas pipeline	construction Norud Stream gas pipeline	approval for construction by Mongolia governm	construction Yamal Europe gas pipeline	EUR： change into gas energy	CHN： strengthen gas infrastructures	CHN： gas domestic demand expanding	CHN： development domestic gas field	CHN： oil domestic demand expanding	CHN： development gas field in Central Asia	US Exim bank: destruction financing contract	construction Beijing Root pipeline
Gazprom： bidding for Rosneft's stock		1		1														
Gazprom： increasing difficulty for earning																	1	
Rosneft： obtaining interest of gas field in Far East																		1
Rosneft： obtaining interest of gas field in East Siberia																		1
countermeasure global warming											1							
CHN： economic development													1		1			
CHN： gas demand increase in urban area												1		1		1		
conflict between China and Russia																		-1
difficulty for constructing in longitudinal Korea Peninsula																		1
conflict in Korea Peninsula																		-1
USA：economic punishment for Iran	-1		-1															
construction for Beijing Root Pipeline					1	1			1									

Fig. 38.2 Cognitive map: period (1-2) (Partially shown)

- Period (1-5): Ukraine crisis ・ Economic sanctions (1-5-3)/Strengthening Russia-Japan cooperation (1-5-1, 1-5-2, 1-5-4, 1-5-5) (Table 38.2).

38.3 Quantitative Analysis: Text Analysis

38.3.1 Methodology

Quantitative analysis was performed using the functions “extraction word: co-occurrence network” and “coding: cross tabulation” of KH Coder’s function.

The function “extracted word: co-occurrence network” is similar to “extracted word: hierarchical cluster analysis”, and automatically draws a diagram that connects highly co-occurring words and phrases based on the sentences of the information source. This co-occurrence refers to the closeness of the appearance pattern of a word, and a diagram showing this relationship is called a co-occurrence network diagram. In this process, the list of related factors created in the process as used as the information source for creating the network diagram. A group of words connected

Table 38.2 Top related factors of cognitive structure map "Yamal LNG Project" (Partially Shown)

NO. term		Related factor	Frequency
1-1-1	term (1-1)	Construction Beijing Root pipeline	10
1-1-2	term (1-1)	RUS: development new gas field	7
1-1-3	term (1-1)	CHN: increase gas demand in urban area	3
1-1-4	term (1-1)	RUS: advance Asia Pacific Area	3
1-1-5	term (1-1)	RUS: privatization domestic oil companies	3
1-1-6	term (1-1)	RUS: strengthen for gas exporting	3
1-2-1	term (1-2)	Construction Beijing Root pipeline	6
1-2-2	term (1-2)	RUS: conflict for Ukraine	6
1-2-3	term (1-2)	Cooperation between Gazprom and CNPC	5
1-2-4	term (1-2)	RUS: economic dependent for resource	4
1-2-5	term (1-2)	RUS: attending for LNG market	4
1-2-6	term (1-2)	Cooperation between NYK and Sovcomflot	3
1-2-7	term (1-2)	Resource development cooperation	3
1-2-8	term (1-2)	Economic cooperation between Russia and China	3
1-2-9	term (1-2)	RUS: adjustment gas exporting price	3

by people with high co-occurrence is called a related factor. In addition, it is possible to create a diagram based on another parameter as a function unique to this function. In this study, the parameter is the 5 periods, and the characteristics of each period are identified (Fig. 38.3).

38.3.2 *Result (Sakhalin-2 LNG Project)*

Summarizing these results, the construction of basic facilities such as the LNG plant of Sakhalin 2 project will be completed at the beginning of the period (2-5) as the project period, and there will be no significant change in the trends. If the construction of facilities in development projects are completed it is understood that the influence of a third party to LNG trade is unlikely. Next, regarding the temporary freeze of the project by the Russian authorities, which is the biggest turning point of this project, there are many related factors such as environmental assessment, acquisition of LNG technology, expansion of project costs, etc. It is inappropriate to interpret this as pressure for acquiring interests. However, as a result of Gazprom's entry into negotiations and the situation that has led to the securing ownership remains unchanged. On the other hand, not only Russia but Japan, as well as international organizations, have suggested long-term recommendations for inadequate environmental consideration in the Sakhalin region with regard to environmental considerations that directly caused it. In addition, the balancing between the value of the project itself and the project cost due to the rise in the price of crude oil is also unclear (Fig. 38.4 and Table 38.3).

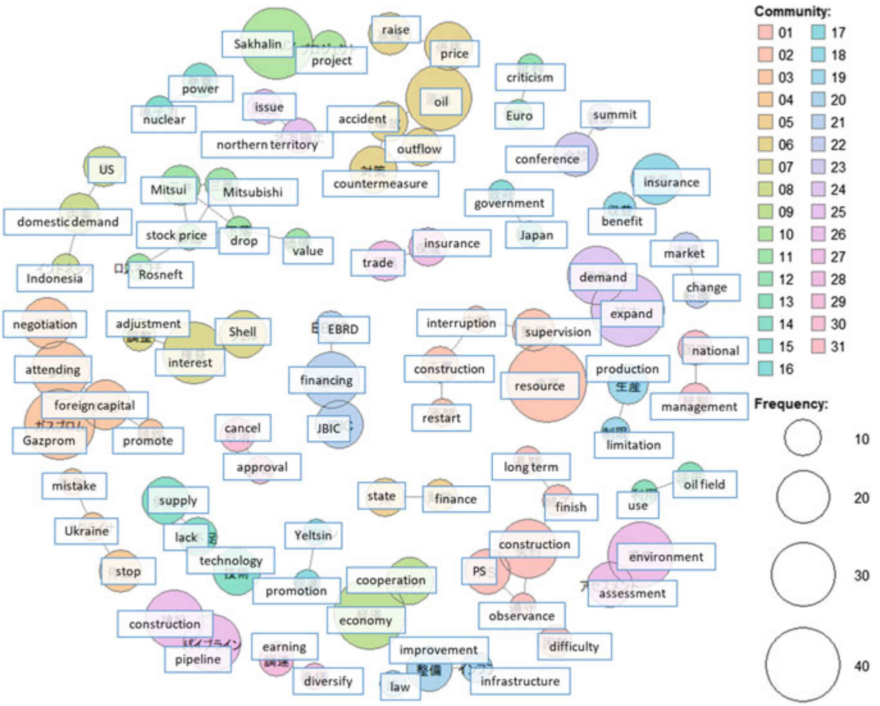

Fig. 38.3 Co-occurrence network diagram "Sakhalin 2 Project"

38.3.3 *Result (Yamal LNG Project)*

The trend of Russia, which switched its center of gravity from Europe to Asia due to various domestic and foreign reasons, overlapped with Japan's direction of benefiting from the fact that LNG was stably secured. To summarize the whole period in three aspects of politics, economy, and technology. The major turning points were the shale revolution and the Ukrainian crisis in the last twenty years. The Shale Revolution resulted in the sharp increase in fossil fuel supply which greatly reduced the dependence of Russia, which has been ongoing since the collapse of the Soviet Union. This made Russia turn resource trade targets into the Asian region. Also, the Ukrainian crisis has triggered a large-scale expansion of China's capital against Russia. On the other hand, the financial and technical aspects were not affected largely, and stable actions such as the construction of the LNG base, indirect financing, and non-dollar financing continued despite the change of the business location (Figs. 38.5, 38.6 and Table 38.4).

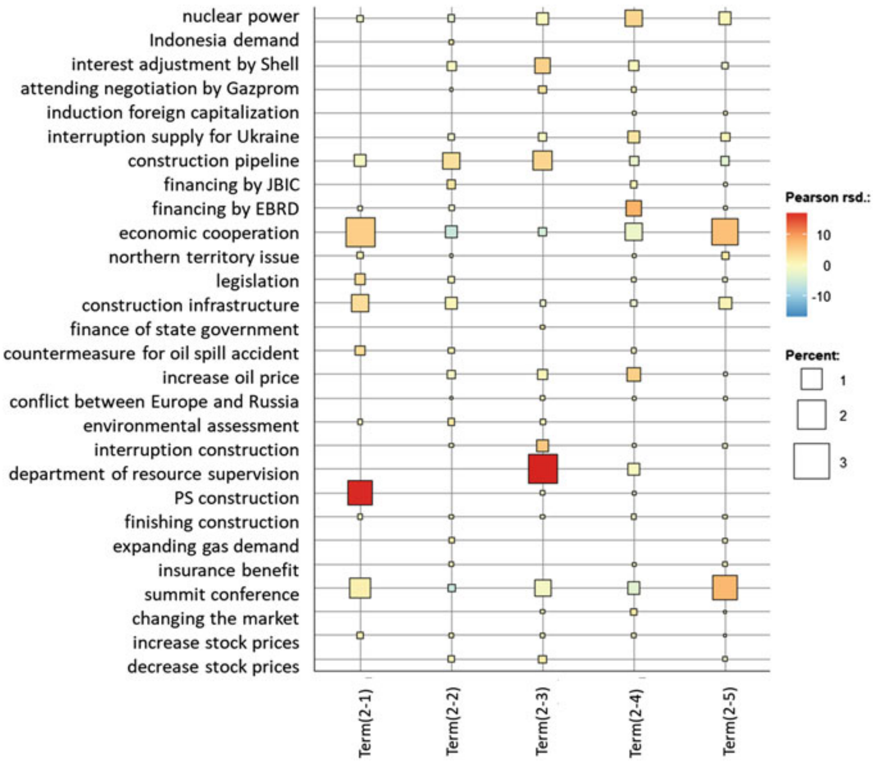

Fig. 38.4 Grouping by term "Sakhalin-2 LNG Project"

Table 38.3 Coding file "Sakhalin 2 Project" (Partially shown)

Related factors	Contents
Nuclear power	Nuclear & generation
US demand	US & demand & natural gas
Indonesia demand	Indonesia & demand & natural gas
Interest adjustment by Shell	Shell & interest & Gazprom
Attending negotiation by Gazprom	Gazprom Gazprom & attending & negotiation
Induction foreign capitalization	Foreign capitalization & induction
Interruption supply for Ukraine	Ukraine & interruption
Construction pipeline	Sakhalin2 & pipeline
Lack of technology	Technology & ability & lack
Financing by JBIC	JBIC & financing
Financing by EBRD	EBRD & financing

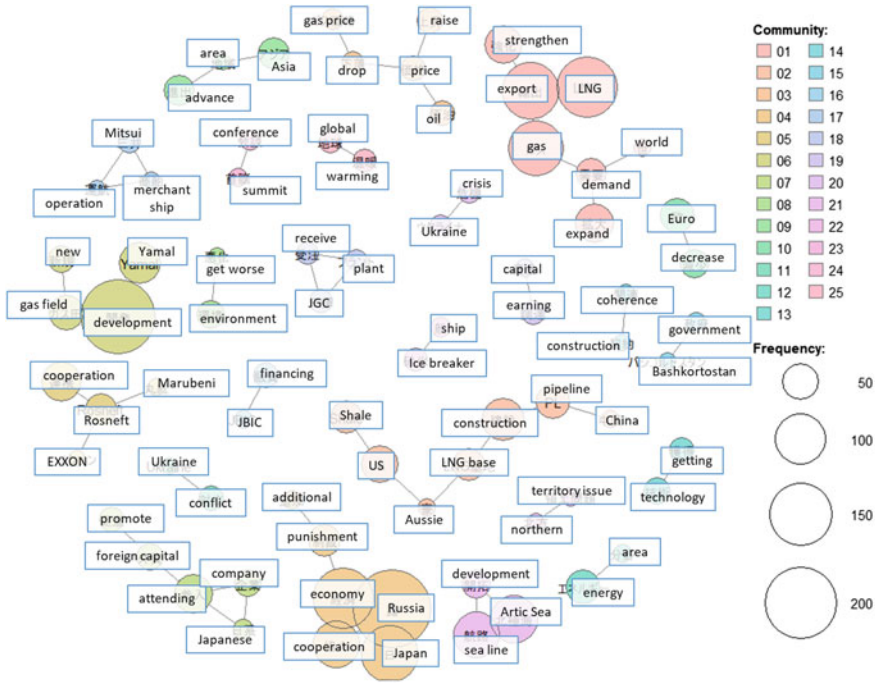

Fig. 38.5 Co-occurrence network diagram "Yamal LNG Project"

38.4 Discussions

38.4.1 Common Points and Differences Between the Two Case Study Results

It is difficult to make a general comparison for these two projects due to the different starting time of the projects and commercialization. But there are still some common and uncommon points.

The common points in these two cases are the first Putin administration's resource nationalism policy, Russia's acquisition of LNG technology, and the worsening of relations with Europe which strengthen its expansion into the Asia-Pacific region. On the other hand, the difference between these two cases is China's entry into business and trends in international oil capital. China has not been encouraged to enter the Sakhalin 2 Project and the Sakhalin 1 Project. Russia was also very cautious about pipeline exports. On the other hand, for the Yamal LNG project, while calling for entry to Japanese general trading companies, etc., it will give Petro China 20% of total interest and add an additional 10% to the Chinese Silk Road Foundation.

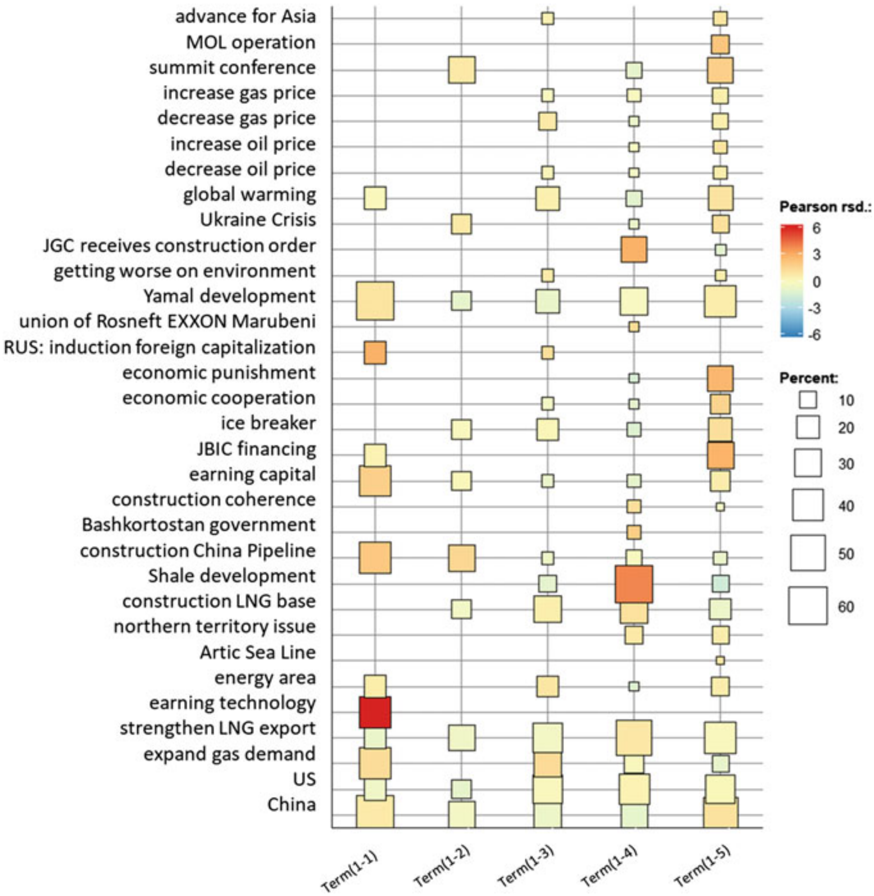

Fig. 38.6 Grouping by term "Yamal LNG Project"

Table 38.4 Coding file "Yamal LNG Project" (Partially shown)

Related factor	Contents
Advance for Asia	Asia & advance
MOL operation	MOL & operation
Summit conference	Summit & conference
Increase gas price	Gas & price & increase
Decrease gas price	Gas & price & decrease
Increase oil price	Oil & price & increase
Decrease oil price	Oil & price & decrease
Global warming	Global & warming
Ukraine Crisis	Ukraine & crisis| Ukraine & conflict

38.4.2 Comparison with Past Studies

Motomura (2009) stated that the cause of the Sakhalin 2 problem was mainly the expansion of project costs and environmental problems. This analysis also shows that Gazprom's acquisition of interest itself has been fixed since before the business freeze. However, after the entry of the Gazprom appearance of environmental issue articles are decreased. But it is difficult to say the entry of Gazprom is the main cause. On the other hand, it can be said that the LNG technology acquired by Sakhalin 2 is the main cause.

38.5 Summary

In this study, we analyzed two LNG projects from the perspective of energy security, economy, technology, and politics. The method of we had developed is combining "cognitive map" and "text analysis" to quantify the qualitative data collected from four major Japanese newspapers during the period of 1991–2017.

Even though, Russian natural gas export strategy shifted from Europe to Asia because of many turning points; Shale revolution, Ukrainian Crisis, and so on. Japans entry into a large-scale business as a stakeholder has high risk. It is desirable to enter in the field such as equipment construction like the Yamal LNG project.

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Chapter 39
Recovery Analysis of Domestic Electric Storage Water Heaters

Emilia Fernández, Carolina Devoto, and Pedro Piñeyro

Abstract In this paper we provide an analysis of the recovery options for domestic electric storage water heaters (DESWH), which are one of the most common devices used to heat water in households of many countries around the world. The analysis considers the characteristics of the product and the condition of its components regarding the functional and safety requirements in order to obtain a remanufactured DESWH that looks as good as new. An inspection guide for determining the adequate recovery option of a used DESWH is provided, with the flow and the detailed description of the operations needed. In addition, we suggest certain recommendations in the design of a DESWH in order to improve its remanufacturing process. The economic benefit related to the DESWHs recovery is illustrated by means of an analysis of the solution obtained from a hybrid production-remanufacturing system that includes the inspection of DESWHs with heterogenous quality and capacity constraints.

Keywords Electric water heaters · Remanufacturing · Inspection · Heterogeneous returns · Optimization

39.1 Introduction

Domestic water heating refers to the process of warming water for personal use. A wide variety of water heating methods are available today, but the most commonly used type in households are storage tank water heaters. A well-suited appliance for demand response is domestic electric storage water heater (DESWH), because of their capability to store thermal energy. In the 1990s about 45 million of these devices were installed in the EU, whereas 33.6% of them were located in Germany (Lübkert et al. 2017). These appliances are the most common type of system for residential water heating in Canada (Aguilar et al. 2005). DESWHs are the most common method for satisfying hot water demand in Uruguayan homes, reaching 80% compared to other ones (Elenter 2018).

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The operating principle of these devices is to heat water in a tank so that a certain quantity of hot water is stored and available when needed. Unheated water then flows into the tank to replace the used water. The thermostat controls the water temperature in the storage tank, turning on the electrical resistance in order to maintain the desired temperature inside the tank (Energy Education 2019; Natural Resources Canada's Office of Energy Efficiency 2012). DESWHs are equipped with different safety devices such as a thermal fuse and pressure relief valve. The thermal fuse responds to temperature, interrupting the electric current when the temperature exceeds a fixed value. Therefore, it provides protection in case of overheating due to malfunction. The relief valve is designed to relieve the pressure inside the tank when a fixed limit is exceeded. The water that flows into the tank generally contains calcium and magnesium that can precipitate and coat the heating elements and pipe surfaces, therefore, dropping energy efficiency. We note that not only is the lifespan of the DESWH reduced, but also it can produce bacterial contamination (Brazeau and Edwards 2011; Lacroix 1999).

In order to minimize corrosion within the tank, a sacrificial anode rod made either of aluminium or magnesium alloy is placed into the tank. The anode is consumed over time so it should be checked regularly and changed when necessary. There is an insulation between the tank and the outer case, which is usually made of polyurethane foam or glass wool. Its function is to maintain the temperature of the interior tank, avoiding as much as possible heat losses through the surface and therefore improving energy efficiency. The storage tank is usually made of copper or steel. Copper is malleable and straightforward to work, whereas stainless steel is harder to drill and welds at higher temperatures requiring more sophisticated manufacturing processes. Besides, copper has lower rates of corrosion (Armstrong et al. 2014). However, copper is a much more expensive raw material than steel.

Increase in the use of home appliances in the recent decades has attracted the attention of governments and civil organizations due to the negative impact on the environment of discarding these types of products at their end-of-life (EoL), in addition to the shortage of landfill space (Heydari et al. 2017). Technological advances and the search for greater comfort have caused that the amount of waste from electrical and electronic equipment (WEEE) has increased dramatically. According to (Balde et al. 2015), the total amount of global WEEE was 47.8 million tons in 2017 and it is expected to reach 50 million tons in 2018. WEEE is the fastest growing waste stream in many countries of the world. They have a dangerous and toxic nature, and therefore an adequate EoL management is essential for them. It is estimated that at least 90% of the materials on these devices can be recovered, such as copper, iron and plastic. However, nowadays less than 20% of them are handled in a proper way (Salhofer et al. 2015; Long et al. 2016). Uruguay is one of the countries in the region that produces more WEEE, with an estimate of 9.5 kilos per year per capita and only 1.5% of them are recovered (CEMPRE, Electrical and electronic devices (in spanish). Available at: http://www.cempre.org.uy/index.php?option=com_content&view=article&id=87&Itemid=105 [Accessed 29 Aug 2019]). In Uruguay, the legal framework related to environmental management follows global trends in sustainable development. There are regulations for the treatment of used tires as well as non-returnable packaging. However, there is currently no specific regulation for WEEE, which usually ends up in public landfills. A bill has been proposed in the Uruguayan Parliament (Proposal of law for the integral management of waste (in spanish). Available at: https://www.impo.com.uy/bases/leyes/19829-2019 [Accessed 30 Aug 2019]) that encourages the proper management of certain types of waste, among them the so-called special waste that includes WEEE. It is important to note that the bill also establishes an extended responsibility to manufacturers, who must take over the management of the waste caused by their products.

Home appliances are rich in valuable materials that can be extracted if the product has good engineering. This has caught the attention of manufacturers, who see an economic opportunity in the recovery of used products in addition to the environment benefit involved (Li et al. 2018). As far as we know, the recovery of DESWH has not been considered in the literature on production systems with recovery options, despite the recovery potential of the product as we will see later in this paper. Recovery is also beneficial for customers, as they can obtain a recovered unit at a lower price and that looks as-good-as new. In addition to failures in the DESWH, there can be other motives for replace his used DESWH. For example, the capacity of the storage tank is no longer adapted to their needs or because the energy efficiency has decreased significantly.

In this paper, we present an analysis of the recovery options for used DESWHs. The analysis is based on a research conducted for Rivomark (https://rivomark.com), a DESWH manufacturer from Uruguay established in 1950. The main contributions of this paper are as follows. We show the recoverability of DESWH based on an analysis of the characteristics of the product and its main components. We consider functional as well as safety requirements of the product. As a result, we suggest an inspection guide for determining the quality level and the proper recovery route for a used DESWH. In addition, we provide certain design suggestions in order to improve the remanufacturing process of a used DESWH. Finally, we analyse the impact of the recovery options of DESWH by means of a mathematical formulation and a numerical experimentation of a hybrid production-remanufacturing system that involves inspection of heterogenous returns, multiple items and capacity constraints.

The remainder of the paper is organized as follows. Section 39.2 describes the methodology for the research conducted and presented in this paper. Section 39.3 presents the recovery analysis carried out for used DESWH, including the inspection guide suggested with the details of the operations needed and the design suggestions for the product. In Sect. 39.4 we present the study of the hybrid production-remanufacturing system for evaluating the impact of the recovery options. Section 39.5 presents the discussion of certain aspects for driving remanufacturing of DESWH and Sect. 39.6 finishes the paper with the conclusions and guidelines for future research.

39.2 Methods

The research presented in this paper was mainly carried out through the following three activities: (1) A survey for existing local and regional regulations about EoL management of products. In particular, we focus in regulations on inorganic solid waste, and WEEE. (2) Interview with experts from the academy, as well as from the public and private sectors, to obtain information on the recovery capacity of DESWH. We investigate about different aspects of the product, such as the disassembly options or the hydraulic and corrosion tests, but also on economic and business characteristics. (3) A bibliographic search on planning problems of hybrid production systems with recovery options, focused on quantitative methods and mathematical formulations and its resolution.

In addition to the activities described above, we conducted a survey through social networks to know the public's opinion on the recovery of DESWHs. We obtained 450 responses, of which 80% expressed their willingness to return a used DESWH, if there was an option to do so. It is also worth mentioning that at all times we kept in touch with Rivomark staff, who shared their knowledge with us and provided the necessary information for conducting the work presented in this paper. This was particularly important for the study presented in the Sect. 39.4 about the hybrid production-remanufacturing system.

39.3 Recoverability Analysis of Deswh

In this section we provide the recoverability analysis of used DESWHs that includes the identification of the most critical and valuable modules of a DESWH. On that basis, we evaluate the feasibility of remanufacturing DESWHs, and we suggest an inspection guide with the order and description of the operations needed. Finally, we provide design suggestions to promote remanufacturing. Remanufacturing involves several analysis fields such as the evaluation of recoverability, re-design of product to facilitate the remanufacturing processes, the research on the necessary operations for the reconditioning of the product as well as an environmental and economic assessment (Tchertchian et al. 2011).

Certain characteristics of the product can affect the remanufacturing process in a positive or negative way. Thus, there are products that are better suited for remanufacturing (Prendeville et al. 2016). Some of DESWHs' characteristics that make it suitable for remanufacturing are: (1) its durability to withstand multiple life cycles, (2) its slow pace of technology evolution, (3) not being subject to fashion or status-related purchasing decisions (4) its high residual value, (5) its modular design and (6) its relatively low number of components with a high degree of recoverability. To study the DESWH recoverability, a practical exercise was carried out to analyze how well the DESWH can be disassembled. The aim is both to identify the best way to recover it and to find the design issues that hinder and aid the remanufacturing process.

Modular design makes product recovery more efficient and profitable. The remanufacturability of the products depends on the critical and most valuable modules (Liao 2018). Therefore, we assess the value and the significance of the different modules that compose a DESWH. Table 39.1 depicts the different components of a DESWH and its estimated costs, depending on whether the storage tank is made of copper or steel. Using the Pareto principle (also known as the 80/20 rule or few vital products law) we can conclude that only a few components account for most of the total cost. This analysis is depicted in Fig. 39.1. Left vertical axis in Fig. 39.1 represents the cost of the components and the right vertical axis the cumulative percentage of the total cost of them. We can appreciate that, for a DESWH with copper tank, the first three components, approximately 23% of the total quantity of components, represents around 75% of the costs incurred. According to Table 39.1, these components are the copper tank, the outer case and the resistance and anode. In the case of a steel storage tank we can note from Fig. 39.1 that the first four components represent around 75% of the costs incurred and these components are the steel tank, the outer case, the resistance and anode, and the safety devices.

Considering both costs and recovery potential of the main components we can conclude that the storage tank is the most critical and valuable module. In addition, copper tanks are more recoverable than those made of steel since they have lower rates of corrosion. In fact, the copper represents almost the 50% of the total components cost of a DESWH. Thus, this component involves a great opportunity from the point of view of recovery. The other components from most to least valuable are the outer case, the resistance, the safety devices and the insulation. The outer case and the

Table 39.1 Costs of the components of a DESWH with a storage tank of copper/steel

Component	Description	Cost in U$S (copper/steel)
CM1	Tank	72/24
CM2	Outer case	24
CM3	Resistance and anode	12
CM4	Safety devices	12
CM5	Insulation	10.75
CM6	Service cover, cable gland and knob	5
CM7	Cables	2
CM8	Labels	1.5
CM9	Pipes	02/1
CM10	Ring tubes and washers	1
CM11	Light bulb	1
CM12	Nipples	0.6
CM13	Screws	0.45

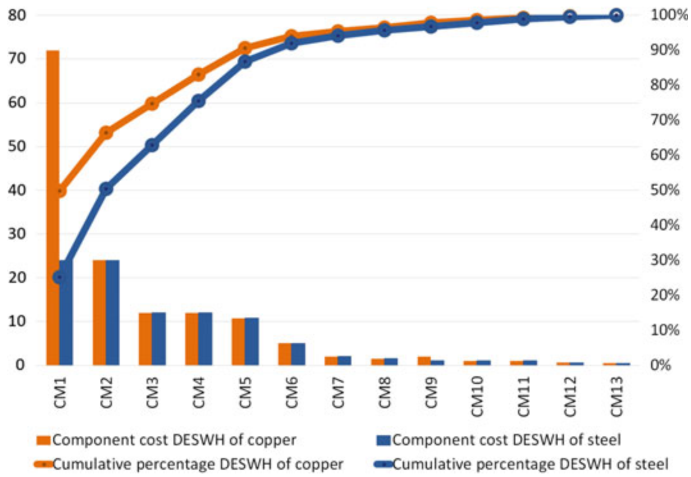

Fig. 39.1 Pareto chart of the components used for manufacturing a DESWH with copper tank and with steel tank weighted by the cost

insulation can be recovered when destructive disassembly is not necessary. As in the case of the resistance, its functionality must be evaluated to decide if it can be reused or must be reconditioned. However, we note that safety devices must always be replaced by new ones, given the severe consequences in case of failure.

Based on the analysis of above, we are able to conclude that the DESWH is a well-suited product for remanufacturing. As it is noted in (Gray and Charter 2006), in order to establish a strong business model of remanufacturing, it is necessary an adequate process for the return of used products, i.e. the design of the reverse network. An alternative is to open collection centres. This requires to determine the number, location and capacity of the centres, according to the amount of reverse flows as well as the installing and operational costs. Another alternative is that retailers receive the used DESWHs and then transport them from the retailers to the factory. We have mentioned here only two possible alternatives, but a more detailed analysis is needed on this matter, which is out of the scope of the work presented in this paper.

39.3.1 Inspection Guide

The inspection guide suggested in this section is focused on the most critical components of a DESWH, since its recovery options depend largely on the recoverability of its critical modules. As it can be appreciated from the cost analysis presented in the previous section, the most critical modules and the ones that are able to be remanufactured of a DESWH are the storage water tank, the outer case and the electrical resistance.

We suggest below a guide for the inspection process of a used DESWH in order to determine whether it is or not remanufacturable, and to what extent.

Step 1—External review: Thoroughly examine the outside of the DESWH for any signs of corrosion, denting or breakage. If there is corrosion, grade the DESWH as non-remanufacturable. If there is not corrosion, but there is an appreciable dent or break, go to Step 2.2. Otherwise, go to Step 2.1.

Step 2.1—Non-destructive disassembly: Open the DESWH in order to access the storage tank. Go to Step 3.

Step 2.2—Destructive disassembly: Remove the outer case and the insulation coverage of the DESWH in order to access the storage tank. Go to Step 3.

Step 3—Hydraulic test: Verify the tank can resist a critical pressure value without suffering water loss for a certain period of time. If it is, go to Step 4, otherwise grade the DESWH as non-remanufacturable.

Step 4—Rust evaluation: If the sacrificial anode and/or the inside of the tank show hints of corrosion, go to Step 5, otherwise grade the DESWH as remanufacturable. End.

If the anode is completely consumed, this will be a sign that the tank is corroded. In this case the condition of the tank cannot be guaranteed, and a second level rust evaluation must be carried out. Go to Step 5.

Step 5—Rust study: Carry out a non-destructive study in order to determine if the tank is or not corrupted by rust. If it is not, grade the DESWH as remanufacturable, otherwise grade it as non-remanufacturable. End.

From Step 3, we note that in order to grade a used DESWH as a remanufacturable, it must verify the hydraulic test. Compliance is verified by subjecting the device to a hydraulic pressure equal to twice the nominal pressure. If the DESWH is fed by means of a pressure reducing device, instead of subjecting the DESWH to pressure, it is subjected to twice the service pressure (Standard UNIT-IEC 60335-2-21:2012 with adoption of UNIT in 2015 Safety of household appliances and similar ones—Part 2: Particular requirements for storage water heaters). The hydraulic test of Step 3 should be the same that the one carried out for a newly manufactured DESWH. The conformity of the test guarantees that the tank is not punctured and that the original structure is maintained.

To carry out Step 5, there are different alternatives, but here we propose two of them. One of them is to measure the corrosion between the anode and the point on the surface that is presumed most affected. Through a quantitative study it is possible to obtain the difference of potentials, and thus estimate the internal DESWH corrosion. Another feasible procedure for the non-destructive rust study of the tank is to measure the thickness of the most affected area by the oxide, for example using an ultrasonic thickness gauge, and compare the value obtained with a nominal thickness value.

In order to summarize the inspection guide of above, a diagram is provided in Fig. 39.2. The diagram depicts the flow of activities in order to determine the quality level of a used DESWH returned to the origin. Boxes and arrows in Fig. 39.2 represent the steps and the order of them. Dashed lines as well as dashed boxes indicate the classification of an inspected DESWH, i.e. remanufacturable or non-remanufacturable.

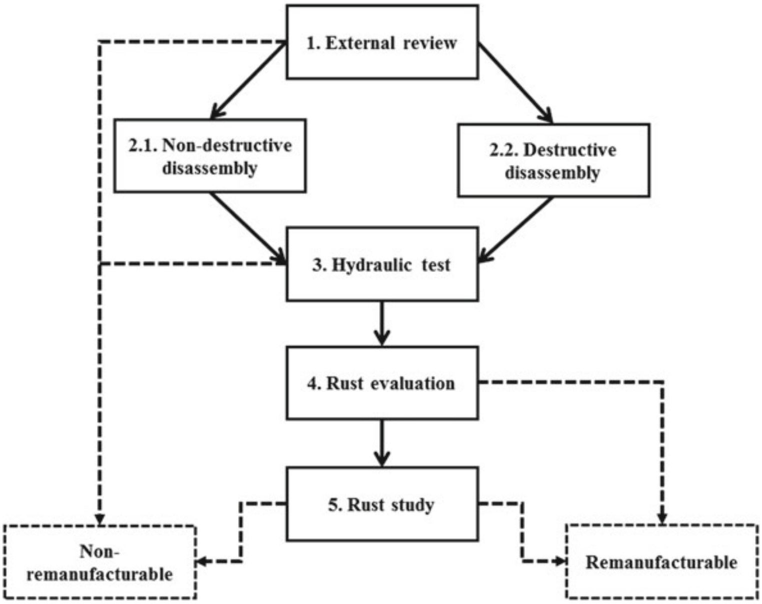

Fig. 39.2 Order of inspection activities and classification on a used DESWH

A used DESWH can be classified as non-remanufacturable for different motives, e.g. by any sign of damage in the outer case detected in step 1, or by an unfavorable rust study in step 5. In the last case, we note that higher inspection costs are incurred. On the other hand, a used DESWH is classified as remanufacturable if after disassembly (destructive or non-destructive), both the hydraulic and rust tests are surpassed, and, if it is necessary the second rust study. We note that DESWHs that require destructive disassembly are of worse quality than those that do not require it.

Thus, through inspection the returns can be graded into different levels of either remanufacturable or non-remanufacturable returns. In order to obtain a remanufactured DESWH, several recovery tasks must be carried out, which depend on the quality level of the return. These tasks include: (1) the decalcification of the tank, (2) the replacement of safety and electrical components, and (3) reconditioning the outer case or installing a new one if it was removed in the destructive disassembly during the inspection process.

39.3.2 Design Suggestions

Remanufacturing process is affected by the physical characteristics of the product, whether the product has been designed considering future recovery or not. The most effective way to promote the remanufacturing is through the product design approach.

Design for remanufacturing can identify and prevent inefficiencies in the process (Prendeville et al. 2016). In addition, disassembly can be considered a critical task since it connects product returns with product recovery, and a prerequisite for some of the tasks of the recovery process (Aksoy and Gupta 2010). Therefore, considering the disassembly operations involved in the inspection guide suggested in Sect. 39.3.1 for a used DESWH, we provide below certain improvements in the product design in order to facilitate them.

The recoverability of a used DESWH depends to a large extent on the condition of the internal walls of the storage tank. The sacrificial anode plays a key role in tank protection because it minimizes corrosion inside. Therefore, an adequate maintenance of this component extends the lifespan of the DESWH. If the anode is not checked and replaced regularly, protection against corrosion is lost. Also, the efficiency decreases drastically as the internal surfaces begin to accumulate layers of lime. The formation of lime depends on the hardness content and the alkalinity of the water. Likewise, the magnesium anode is in its dissolution a source of hardness.

In general, the anode and the electrical resistance are placed together centred in the lower part of the tank. This design reduces energy efficiency due to the formation of scale around the anode, and therefore, around the resistance. In addition, it prevents the anode from being easily checked and replaced without performing a maintenance to the resistance. The location of the anode is, therefore, a factor that must be considered to improve the design of the product in view of recovery. Thus, we suggest the following redesign recommendations for avoiding these problems. One of them consists of placing the anode separated from the resistance. Hence, the anode could be checked without having to perform a maintenance to the resistance and guaranteeing the transmission of heat to the water. Another option is to place two anodes screwed independently at the top and bottom in opposite corners of the tank and separated from the resistance. The advantages of having two sacrificial anodes is that it maximizes the anticorrosive protection inside the tank, thus prolonging the lifespan of the DESWH and simplifying the revision and replacement of the anodes. We note that the increase in manufacturing costs by incorporating another anode is at most U$S 10, which makes it economically beneficial considering the best quality of the future returns and therefore the lower recovery costs. We consider important to mention that any of these design suggestions facilitate also repair and maintenance operations.

As we mentioned above, the accumulation of lime inside the storage tank reduces it lifespan. An alternative to reduce this negative effect is to use a water softener that removes calcium and magnesium from the water before it flows into the tank. However, this may be difficult to implement, so it may be more appropriate for users to perform a frequent maintenance of the DESWH in order to prevent lime accumulation.

Finally, we analyze the two materials used most often for the insulation of a DESWH: polyurethane foam and glass wool. The sealant property of the polyurethane foam simplifies the union and stability of the surfaces of the DESWH. However, this property causes the foam to break down when it is detached from the tank, therefore causing greater dismantling costs, and in addition the material cannot be recovered. On the other hand, polyurethane has better energy efficiency than the glass wool, but the later can be removed easier than the former, simplifying thus the process of dismantling. Therefore, glass wool brings more benefits for EoL of the product than polyurethane foam. We note that way to simplify the dismantling process is to put a nylon layer between the tank and the insulation, to avoid polyurethane sticking to the tank.

39.4 Hybrid Production-Remanufacturing System

In this section we describe the hybrid production-remanufacturing system proposed to evaluate the impact of including recovery options for DESWH. Hybrid production-remanufacturing systems refer to production systems in which the demand requirements of an item can be also satisfied by remanufacturing used items returned to the origin. This hybrid system can be modelled as a Mixed-Integer Linear Programming (MILP). This MILP consists of an objective function for minimizing the sum of the costs involved and a set of equations and inequations for establishing the constraints of the problem, all them composed by linear expressions of certain variables and parameters. To solve the model and thus determine the optimal values of the variables, it is necessary to provide the values of the problem parameters. In this case it involves the values of the demand, returns and the costs for both holding inventory and carry out the production activities. We note that the current production system of Rivomark does not consider recovery options. Therefore, the values of the parameters related to the returns were estimated based on the analysis of recoverability of DESWHs presented in Sect. 39.3. The other values required for the model were estimated along with Rivomark.

39.4.1 Problem Description

We consider the dynamic demand requirements of multiple items (i.e., different DESWH types) over a finite number of periods, that can be satisfied by producing new items or by remanufacturing used items returned to the origin. The condition of the incoming returns is assumed diverse (heterogeneous returns) and an inspection activity is required to determine their quality. The inspection process is that provided in Sect. 39.3.1. Through inspection, the returns are graded into a finite number of nominal quality levels of non-remanufacturable and remanufacturable items (inferior and superior qualities). Two and five quality levels are considered in this study for remanufacturable and non-remanufacturable returns, respectively. Remanufactured and new products are assumed perfect substitutes despite the heterogeneous quality of the incoming returns, i.e., remanufactured products look as good as new. Unit costs are incurred for holding inventories of returns as well as serviceable products. Separate inventories are considered for incoming as well as inspected-and-graded returns and for serviceable products. Set-up and unit costs are assumed for production, remanufacturing, discard and inspection of returns. Costs related to returns depend on their quality: top qualities imply higher costs for inventory and lower costs for remanufacturing and discard. Demand and returns quantities as well as the different cost values are assumed known in advance for each one of the periods within the planning horizon. The objective is to determine the quantities to be inspected, remanufactured, discarded and produced at each period in order to meet the demand requirements on time, minimizing the sum of all the involved costs.

39.4.2 Description of the Mathematical Formulation

The hybrid production-remanufacturing system stated above can be modelled as a Mixed-Integer Linear Programming (MILP). We provide below a description of the objective function and constraints of the model. The detailed MILP formulation can be found in (Devoto and Fernández 2019). We also note that it can be considered an extended version of that presented in (Devoto et al. 2019) for a hybrid system of a single item and without capacity constraints.

- Objective function: sum of the costs related to the production, remanufacturing, discard, inspection and holding inventories.
- Constraints to establish that a set-up cost is incurred whenever a positive amount is produced, remanufactured, discarded or inspected.
- Inventory balance equations for serviceable, incoming returns and inspected-and-graded returns.
- Initial inventory equations.
- Capacity constraints for the inventory of serviceable items and for the production and recovery lines.
- Specific constraints of Rivomark about the type of products that can be produced and/or remanufactured in the same period.
- Constraints for rounding the quantities of graded returns.
- Set of domains for the variables (continuous, integers and binary values).

We note that the MILP formulation has $(I \times T + Q \times I{\times}T + T)$ variables and $(Q \times I{\times}T + Q \times I + I \times T)$ constraints, where T is the number of periods, Q the number of quality levels, and I the number of products.

39.4.3 Resolution Procedure and Analysis of Results

In order to evaluate the impact of including recovery options, we compare the solution obtained with the model of above for the hybrid system, against the solution of a MILP model developed for the current production system of Rivomark without returns options. More specifically, we compare the costs of holding inventories and carrying out production activities related to new and returned products. Given the computational complexity to solve a MILP of a production system that involves capacity constraints and return options (Bitran and Yanasse 1982; Retel-Helmrich et al. 2014), for the numerical experimentation we consider only the information of a certain period of time that is representative and that resulted in a planning horizon of $T = 21$. In the case of the model for the hybrid system, we add a new family of constraints for considering only those solutions for which the inspection of returns in certain period involve all the available returns of the same quality. The convenience of this decision is supported by the findings of (Devoto et al. 2019) over a hybrid system of a single item. In addition, the safety stock level of final products was estimated as one third of the level of the current production system without returns, since in the hybrid system there are three different production lines of products (one for new products and two for remanufacturable products).

The values of the parameters used in this study for both models were estimated based on historical data of the firm. Returns were estimated as the 60% of the demand values. Models were coded in AMPL and solved with solver Gurobi 8.1.0 on a PC with Windows 10, CPU i7-4710HQ, 2.50 GHz and 16 Gb of RAM. The running time of the solver was limited to 17 h, since in the 5 h after the first 12 h of execution there was no substantial improvement in the quality of the solution (less than 0.09% in the objective value). Comparing the production and holding inventory costs of the solutions obtained for both models, we note that the saving for the hybrid system is 7.2%. Figure 39.3 shows the distribution of the costs of both solutions. In addition, we want to point out the cost saving observed for the hybrid system may be even greater since, unlike what happens for the solution of the traditional production system, the duality gap (maximum possible gap with an optimal solution) indicates that it is very likely that there is a lower cost solution (8.59 vs. 1.23%).

We refer to (Liao 2018) for details about the models, parameter values and results of this section. Relevant information is also available in https://www.fing.edu.uy/node/36721.

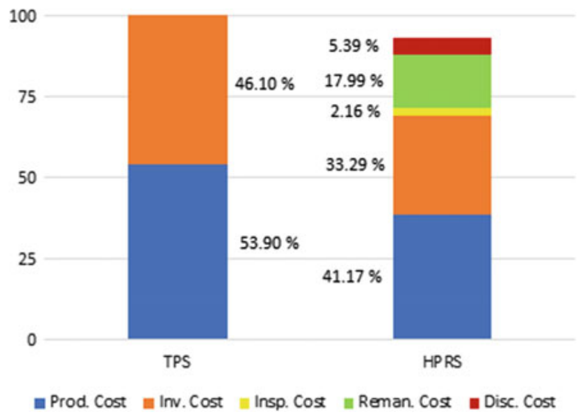

Fig. 39.3 Distribution costs (in percentage) for the traditional production system (TPS) and the hybrid production-remanufacturing system (HPRS)

39.5 Discussion

Considering the findings of the previous sections, we distinguish the following key issues for driving remanufacturing of DESWH: (1) improve the design with view on recovery, (2) encourage good use and maintenance of the product by customers, (3) promote EoL options for used DESWH.

To address point (1), in Sect. 39.3.2 we provide design suggestions with the aim to facilitate and improve the remanufacturing processes of used DESWH. These suggestions can help reduce the recovery costs and thus improve the performance of the hybrid system. With regard to point (2), we believe that a good way to approach it is by means of a scheduled maintenance provided by the manufacturer, in order to adjust or replace the necessary components and warn customers when the DESWH must be replaced. We note that this is a situation of benefit for customers, manufacturer, and environment. Customers avoid situations of failures, even dangerous, due to the malfunction of their DESWH and the manufacturer ensures the supply of returns with the best possible quality. This also has a positive impact on the environment since the amount of waste and extraction of raw materials tends to be reduced. Finally, to address point (3), the manufacturer can provide financial incentives to motivate customers to return EoL products, such as deposit systems, credit toward a new unit, or cash (Zhou and Yu 2011).

39.6 Conclusions

This paper presents a recovery analysis of DESWHs based on a research carried out for an Uruguayan manufacturer. DESWHs are one of the most common devices used to heat water in households not only of Uruguay but also of many countries around the world. From the analysis conducted, we can conclude that the storage tank is the most critical and valuable component of a DESWH. In addition, we note that the copper storage tanks are more recoverable than steel ones, because they are less prone to oxidation. As a main result of the recovery analysis, we suggest an inspection guide for a used DESWH, with the operations needed in order to grade it and thus determine the adequate recovery route. We note that for grading a used DESWH as remanufacturable, both the hydraulic and the rust tests must be performed and complied. In addition, certain design suggestions are provided in order to improve the remanufacturing process of a used DESWH.

We also present the results of a numerical experimentation carried out for evaluating the impact of recovery options in the current production system of the firm. This quantitative analysis was performed by means of designing and solving a mathematical model for a hybrid production-remanufacturing system, which involves multiple items, capacity constraints and inspection of returns with heterogenous quality. From the results obtained, we can conclude that including recovery options in the current production system of Rivomark can lead to valuable economic benefits.

A possible direction for future research is to extend the recoverability analysis to similar products, such as storage water heaters of other energy sources like natural gas and oil. Regarding the hybrid production-remanufacturing system, it would be interesting to design and evaluate more efficient resolution procedures, than the solving method considered here for the mixed-integer linear programming formulation suggested for the problem. In addition, as it is mentioned at the beginning of the paper, study the design and configuration of the reverse logistics network for DESWH is an interesting issue for a future research.

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Chapter 40
Feasibility Study for Electric Vehicle Utilization as Grid Supporting in Indonesian Power System

Muhammad Huda, Koji Tokimatsu, Arif Darmawan, and Muhammad Aziz

Abstract The improvement of electric vehicles (EVs) selling growth in the last decades also shows the global attention to the climate change. The governments have issued policies and regulation in order to increase the adoption of EVs, such as tax reduction, enlarge charging infrastructure area and facilitate the EV industry to research and development. However, the high penetration of EVs potentially causes stress to the power grid. It can happen in case that the supply cannot cover the unpredictable demand from EVs charging. It is very important to improve the grid capability for balancing its grid conditions due to increasing fluctuating supply and load, such as wind and solar energy. In addition, massive charging of EVs potentially worsen this condition due to significant fluctuation and large gap in the load profile between peak and off-peak periods. The participating opportunities in grid ancillary services have encouraged the idea to use the battery of EVs as a highly responsive power storage in the power system. The techno-economy of vehicle-to-grid (V2G) in Indonesia, especially in Java-Bali grid, is studied in this paper with several the feed-in-tariff schemes. The results show that the peak supply can reduce up to 2.81% (coal replacement) and 8.94% (gas replacement) from driving patterns model. However, V2G potentially increases the generation cost during peak period to 26.5% per month to power company.

Keywords Vehicle-to-grid · Peak load shaving · Electric vehicles · Driving pattern · Indonesia power system

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40.1 Introduction

In order to reduce the greenhouse gas (GHG) emissions by increasing the efficiency of fossil-fuel-based power generation systems, as well as installing renewable-energy-based power systems, a concept called as smart grid has been introduced (Dallinger et al. 2013; Tokimatsu et al. 2018). One of the challenges that a smart grid needs to tackle down is the unpredictable power supply and demand. One of the causes of uncertain power supply is the nature of the renewable energy generation systems (e.g., wind-mills and solar photovoltaic systems). On the other hand, one of the causes of uncertain power demand is the penetration of EVs (Zhang et al. 2017; Juangsa et al. 2017). Electricity as a good has special characteristic that is non-storable at least in large quantities, and at an economic cost even if there is battery and hydro storages that is still being developed and expensive (Mitani et al. 2017).

Nowadays, there is a high interest on electric vehicles (EVs), especially in the developed countries, due to their beneficial characteristic including high energy efficiency, minimum maintenance frequency, and environmentally friendly (Li et al. 2016). City car is still common use for commuting in urban area, meaning that it is almost parked during the day. Very large demand of electricity is predicted when EVs are charged at the same time, causing an imbalance in power system (Dubarry et al. 2017). However, in case that both charging and discharging of EVs can be controlled and scheduled, EVs are potential in supporting the grid as distributed energy resources and storage devices (Huda et al. 2018). Therefore, the scheduling and control of both charging and discharging are very urgent to be developed. This developed smart system with mobile energy storage is called as vehicle-to-grid (V2G) or vehicle grid integration system.

40.1.1 EV as Distributed Energy Resources (DERs)

New technologies bring exciting growth in many industries that make a continuous change in way of energy use and its business (Hall and Roelich 2016). These changes can affect a delicate balance of energy supply and demand (Taibi and Fernández 2017). As today, grid struggles to meet the increasing demand for electrical energy problems and faces a risk of decreased productivity and revenue (Jenniches 2018). Power generation, which is scattered around the country, is delivered to the end-user through complex transmission and distribution systems, also known as the grid. These power generation facilities produce electricity using coal, gas, nuclear and, recently, renewable sources like wind and solar (Nunes and Brito 2017). However, the alternative generation to meet the energy demand which is affordable, reliable and clean is using the distributed energy resources (DERs) (Zhang et al. 2017).

DERs can help the energy use to be more efficient by generating on-site and storing it for use during peak operating times (Aziz et al. 2015). Distributed energy includes vast array of small-scale energy technologies owned by consumers, such as rooftop

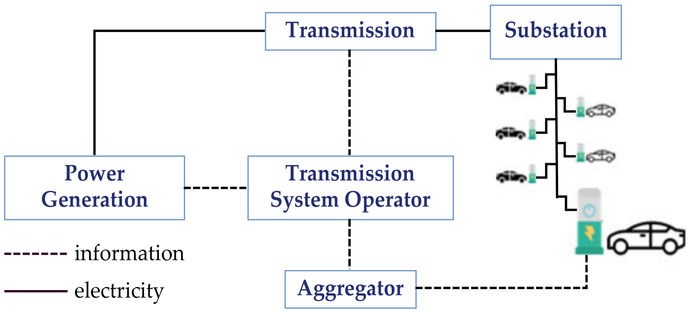

Fig. 40.1 V2G concept

solar, home batteries, electric vehicles and their charging point that communicate to each other and response to signals from the grid (Balamurugan et al. 2012). These alternatives energy resources are connected to the power grid into the household consumers, especially when the grid insufficient to supply their demand, therefore, reduce their electricity bill (Mandelli 2015). In the future, more people own EVs, smart appliance and home energy management system that can coordinate and control their energy use (Gelazanskas and Gamage 2014). These behavior create lot of challenges for the current system to overcome, including how to manage the voltage or predict supply and demand (Gayathri et al. 2015). Figure 40.1 shows a conceptual diagram of V2G as DERs providing ancillary services to the grid.

The integration of all power resources can make electricity network stronger and more affordable (Lund et al. 2017). As well as being renewable, the world future energy trend will be small-scale and largely distributed. There are several considerations to identify the barriers of these system such as consumption pattern, weather condition, and electricity market, which are the important part to take additional benefits of DERs. This study focuses on the feasibility of V2G as distributed energy system that take part to peak load cut based on driving pattern consideration and electricity market model in Indonesia.

40.1.2 Indonesia Power System Condition

Indonesia, representing the developing country, set a target to adopt high portion of new and renewable energy, and reduce the fossil fuel usage as spinning reserve. However, the country still commits to develop coal power plants to support the economic growth (PT PLN (Persero). PLN Statsistics. 2017; Prananto et al. 2018). The fossil fuel usage has been dominating the energy mix that contribute to 37.7% and 41% for fuel cost of coal and gas, respectively, as shown in Fig. 40.2 (Ren DIR, Pln PT. RUPTL PT PLN (PERSERO) 2018:2018–27). On the other hands, peak demand on the whole day still occurs in the certain time that causes a big gap

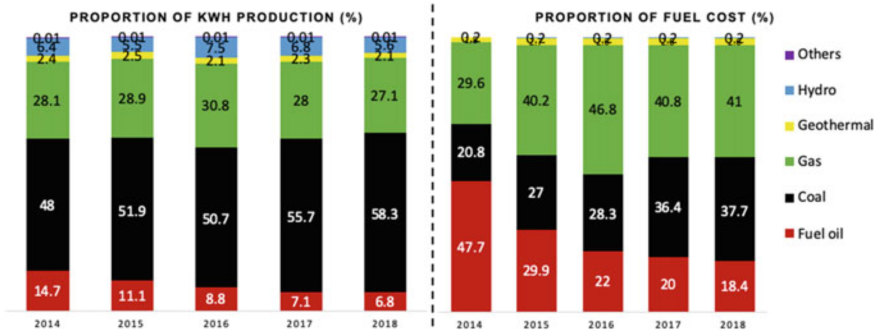

Fig. 40.2 Contribution of fuel sources in Indonesia power system

between peak and valley in the load profile, therefore, this gap is covered mainly with the fossil fuel such as natural gas.

Electric demand is influenced strongly by economic activities, population, lifestyle, and seasonal conditions. Therefore, it can be considered a sign of national economic growth (IEA 2015). *Perusahaan Listrik Negara* (PLN) as a state-owned company for electricity is the main decision maker for all infrastructure development of electricity and takes the control on electricity transmission and distribution. PLN has a plan to achieve a security of supply by increasing the electrification ratio and setting a reserve margin of 25–30% in the Java-Madura-Bali (JAMALI) area, and of 35–40% in the rest of the country. In addition, the commitment of higher safety and lower production costs are also projected (PT PLN (Persero). RUPTL PLN 2017-2026.pdf. 2017).

To meet the future demand and encourage investment from private sector, PLN is offering future revenue through power purchase agreements (PPAs), in which PLN guarantees a long-term power demand to independent power providers (IPPs) (PT PLN (Persero). RUPTL PLN 2017-2026.pdf. 2017). The forecast of demand depends on the economic situation and other aspects that affect the consumption behavior (Saxena et al. 2015). Indonesia has a significantly growing investment in power generation, with a target that by 2027 approximately 63% of the generation capacity is supplied by IPPs, with an expectation of 6–7% of economic growth (PT PLN (Persero). RUPTL PLN 2017-2026.pdf. 2017).

There are many problems that should be solved with the above condition. The first is the unused demand that is possible to occurs if there is no effort to increase electricity consumption to absorb the oversupply generation. Second, the high penetration of EVs in the future will impact the peak load to be two times higher than before due to unpredictable charging behavior. Last, electric company has to fire up many high ramp rate power plants, such as hydro and gas power generation to meet the demand, that is relatively expensive.

40.2 Objectives

This study aims to review the potential ancillary services of EVs to reduce the peak load by fossil fuel power plant using a techno-economic analysis. The analysis considers feed-in-tariffs optimization to improve the benefits from both sides (EV owner and power supplier). The utilization of EVs in power grid management is studied in this paper to attract the popularity of the V2G concept which is currently popular studies in several European countries and US. Therefore, the implementation of V2G in Indonesia as developing country is also predicted (Taljegard et al. 2019).

40.3 Materials and Methods

40.3.1 Methodology

In order to assess the suitable FITs, the techno-economic study has been conducted, including peak shaving that shows the benefits of V2G from two perspectives: EVs owner and power producer. Several assumptions are set due to limitation of Indonesia's policies regarding EVs and ancillary services in power system, electricity market, and driving pattern of commuter behavior in Indonesia. The proposed method for the techno-economic analysis conducted in this study is shown in Fig. 40.3. Basically, there are four stages in this methodology, including assumption of several technical parameters and a driving pattern, load profile analysis, technical analysis related to potential energy availability and peak load shaving, and economic analysis.

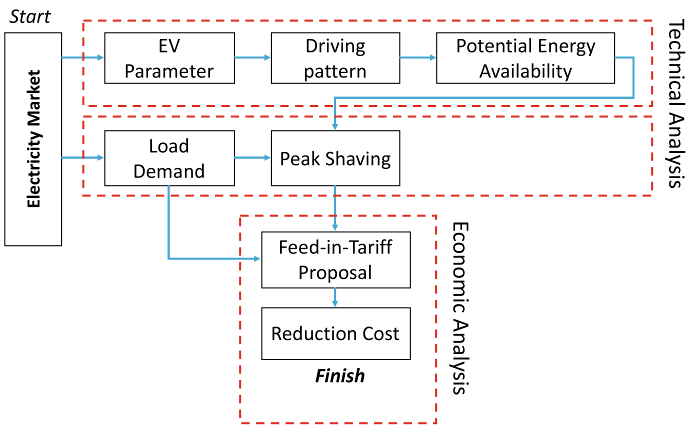

Fig. 40.3 Flow chart

40.3.2 Electricity Market Assumption

The power system must be kept in balance, being produced and consumed in equal amounts at all times (Zhao et al. 2018). This condition is ensured on the electricity market by trading in one-hour cycles that has been implemented in developed countries with demand response (Aziz et al. 2018).

However, the load fluctuation must be covered by a high ramp-rate power generator to return the frequency to its normal value (50.00 Hz) (PT PLN (Persero). PLN Statsistics. 2017). In addition, the peak load basically occurs twice in a day, caused by high demand from several sectors, including industrial (noon peak) and residential (night peak) activities. As the primary regulation, governor-free regulation is adopted to stabilize the frequency, with a dead band range (Δf) of 36 MHz. However, there is a high possibility of disturbance of the power system (out of deadband range) owing to technical or non-technical problems (Huda et al. 2018). This is shown in how many numbers of frequency fluctuation occurred that is represented in Fig. 40.4.

From these results, the electricity market period has been assumed for V2G as DER to support power system and reduce the unpredictable demand. In addition, in this study, analysis on the frequency fluctuation occurring during the day is also conducted to study the potential of the ancillary market for frequency regulation. For these purposes, four periods are assumed in a day, as shown in Table 40.1.

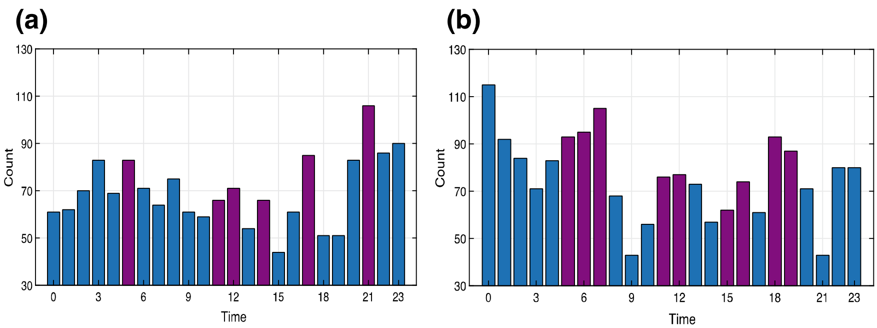

Fig. 40.4 Number of fluctuation **a** $\Delta f < 0.036$ Hz **b** $\Delta f > 0.036$ Hz

Table 40.1 Time period of electricity market

Time	Period
04.00–06.00	1
10.00–12.00	2
14.00–16.00	3
18.00–20.00	4

40.3.3 Feed-in-Tariffs (FITs)

Feed-in-tariffs (FITs) is a policy mechanism designed to accelerate investment in renewable energy technologies. To achieve this goal, the government, as policy maker, offers long-term contracts and higher prices for renewable energy supplier based on the generation cost of each technology and time of use. Currently, PLN as retailed operator is still implemented fixed tariff that provides electricity selling prices for household consumers and 65% of regular tariff to buy the electricity from rooftop solar panel to EV owners in accordance to the current PLN regular tariffs (IDR 1467/kWh), which is equal to 10 ¢/kWh. In this study, the proposed tariff based on cost generation called natural tariffs, is compared with the regular one to attract V2G participation and reduce the cost of charging. Besides, this tariff is expected to be able to improve the generation cost that is mainly covered by fossil fuel.

The natural tariff is obtained from the fluctuation of the cost of the composition of the energy mix, with an additional margin that is close to the average PLN regular tariffs. This tariff is calculated from the fuel cost ($\boldsymbol{P_i}$) and total supply ($\boldsymbol{S_i}$) from each unit power plant of the different fuel resources, which depends on the energy mix for every 30 min. The total generation cost ($\boldsymbol{C}$) from each fuel can be calculated by summing up all unit of the power generators from the different fuel resources with follow definition ($\boldsymbol{j} = \textbf{type of generation}$ such as G: geothermal; CP: coal; CC: combine cycle; H: Hydro; GT: gas turbine; GE: gas engine and $\boldsymbol{i}$ = number of generation units). The total unit of power plants that are involved in this calculation is about 223 units of generator with different type of sources.

$$\text{Total supply} \quad \boldsymbol{S_{tot}} = \sum_{j} \sum_{i=1}^{n} \boldsymbol{S_{ji}} \tag{40.1}$$

$$\text{Cost per fuel composition} \quad \boldsymbol{C} = \frac{\sum_{i=1}^{\boldsymbol{n}} \boldsymbol{P_i S_i}}{\boldsymbol{S_{tot}}} \tag{40.2}$$

$$\text{Natural Tariff} \quad \sum_{\boldsymbol{j}} \boldsymbol{C_j} \tag{3}$$

40.3.4 Input Parameter

To analyze the potential of benefit from technical parameters, several assumptions have been set, including: (a) the forecasted number of EVs will reach to one million in 2035, (b) the chargers have an average capacity of 3 kW, (c) the charger has a loss per pass of 5%, (d) EVs have average battery capacity of 24 kWh with efficiency of 95%, and (e) depth of discharge (DoD) limitation is 85%. In addition, the V2G participation percentage is set to 30%, considering early and developed adoption, respectively as shown in Table 40.2).

Table 40.2 EV parameter

No.	Parameter	Symbol	Value
1	Battery capacity	B_{cap}	24 kWh
2	Charger capacity	C_{cap}	Type 1 (3 kW)
3	Charging efficiency	C_{eff}	95%
4	Charging rate	C_{rate}	24 kWh/h
5	Discharging rate for V2G	D_{rate}	2.85 kWh/h
6	Depth of discharge	DoD	80%
7	Real energy consumption	E_{cons}	9.26 kWh per 100 km
8	Average distnce for travel to work	d	20 km/trip

40.3.5 State of Charging (SoC) of Driving Patterns

To determine the driving patterns, small survey has been conducted for Jakarta's commuter (capital city of Indonesia). Availability of EVs in parking lot is determined by departure and arrival time to commute every day (weekday and weekend). Besides, location of charging point includes discharging system that can sell the electricity to grid is assumed in two location (home and office) with similar capacity.

$$\text{For travel} \quad SoC_t(trip) = SoC_{t-1} - \frac{(E_{cons} * d)}{B_{cap}} \tag{40.4}$$

$$\text{For Charging} \quad SoC_t = SoC_{t-1} + \frac{C_{rate}}{B_{cap}} \tag{40.5}$$

$$\text{For V2G} \quad SoC_t(V2G) = SoC_{t-1} - \frac{D_{rate}}{B_{cap}} \tag{40.6}$$

In case 1, EVs are owned by a private personal as commuting vehicles only in weekday, but there is no V2G connection at the office/company. In case 2, we modify the case 1 with availability in the garage or parking lot on weekend. In case 3, similar to case 2 but with additional V2G connection during noon at the office/company. Moreover, in case 4, EVs are owned by the office or company as operating vehicles during weekday, therefore, they usually move during noon and parked in the office/company from evening to the next day morning and 24 h during weekend. In case 5, EVs are only used during weekend, which possibly occurs in several metropolitans with established commuting transportation system (Fig. 40.5).

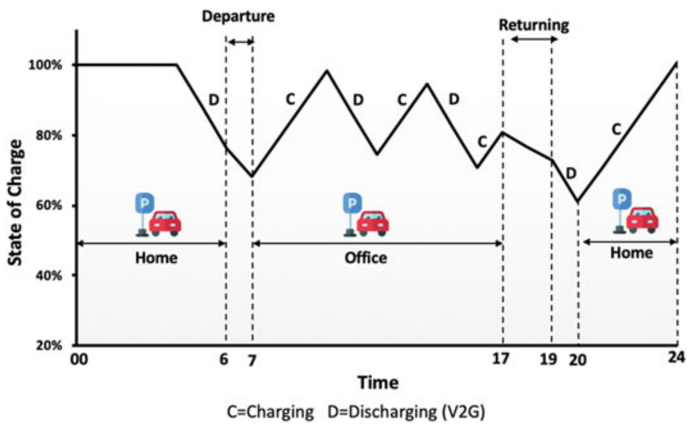

Fig. 40.5 State of charge in case 3

40.4 Results and Discussion

Technical Analysis

40.4.1 Potential Energy Availability

Driving pattern has impacts to the amount of energy that potential to electricity market. SoC is defined as the remaining capacity which could distributed overall day. From original schedule based from survey, the sensitivity has been analyzed from time changing. When EVs depart and arrive more earlier or later, it will change the capacity left that potential to be sold to the power grid. Figure 40.6 shows the amount of capacity and its change from original schedule.

From this results, the pecentage of changing fluctuated with different time variable. As shown in Table 40.3, case 1 most sensitive with time variable and case 5 less impact from this variable. It because, case 5 is mostly parked in a weekday without any schedule to travel. But in case 1, there is only one opportunity (night peak) to sell battery left capacity and it depends on time arrival after work.

40.4.2 V2G as Peak Load Shaving

As peak shaving, EVs can cover the high ramp rate in the peak period via V2G, and can be dispatched to supply electricity to the grid when the demand is high, both during day and night. In addition, they can also absorb the electricity when the

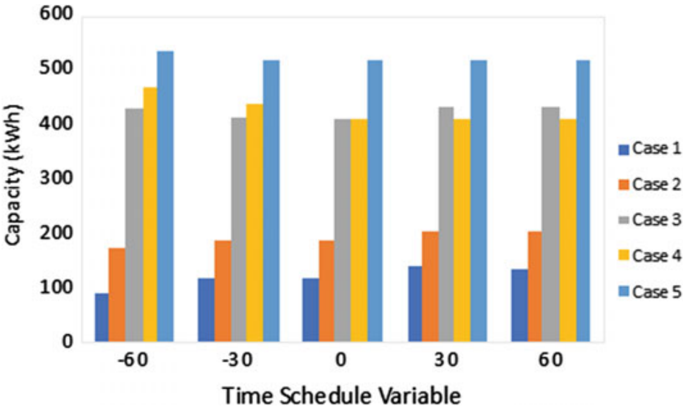

Fig. 40.6 Potential available capacity per EV with time variable from original schedule per month

Table 40.3 Different changing from original schedule

Time variable (min)	Case 1 (%)	Case 2 (%)	Case 3 (%)	Case 4 (%)	Case 5 (%)
−60	−22.90	−6.90	3.40	6.80	2.70
−30	1.20	0.80	1.00	7.30	0.00
30	18.30	11.50	5.90	0.00	0.00
60	−1.00	−0.70	−0.30	0.00	0.00
STDEV	16.90	7.70	2.70	4.10	1.40

demand is low, such as during midnight to morning. Table 40.4 shows the possible contribution for the peak reduction via V2G in all evaluated cases. As can be observed, there is a clear potential reduction of energy demand on the peak period (MWh) in Indonesia via V2G, especially in the JAMALI power system. Case 5, where the EVs are available for both charging (electricity absorption) and discharging (electricity delivery) during weekdays, can provide the largest peak load reduction as compared to other cases (2.8% for coal and 8.8% for gas).

Table 40.4 Energy peak reduction

Cases	Energy from EVs at peak (GWh)		Total peak energy reduction (%) by fuel replacement	
	Day	Night	Coal	Gas
1	0	18.8	0.5	1.6
2	0	18.8	0.5	1.6
3	68.4	18.1	2.4	7.5
4	34.2	35.5	1.9	6
5	68.4	34.2	2.8	8.8

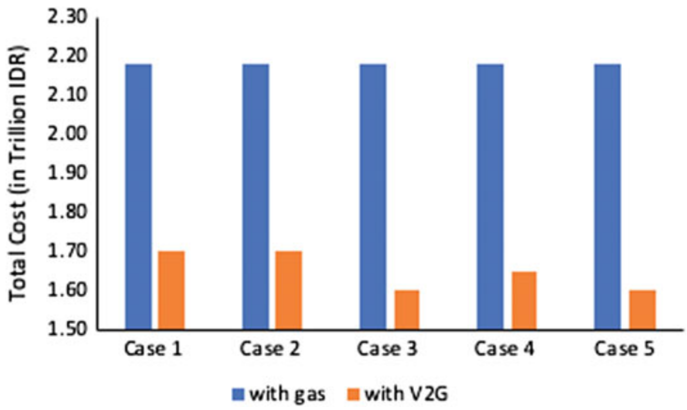

Fig. 40.7 Cost reduction at peak period with natural tariff

Economic Analysis

40.4.3 Potential Reduction of Cost Generation

Figure 40.7 shows the potential revenue improvement from cost generation reduction for the power company (operator) with proposed tariff. Case 5 and case 3, with a natural tariff and gas replacement, leads to the highest annual improvement of approximately 26.5% on peak period for the electric company as compared to other cases. It is caused by the longest V2G participation time as compared to other cases, as the cost of gas fuel, which was reduced, is more expensive than the cost of V2G.

Massive EV adoption and participation in the V2G program can be considered as potential way to achieve a high quality of electricity during weekdays with a stable regulation framework. Coal replacement is not profitable for an electric company, because the generation cost is still cheaper for producing electricity.

40.5 Summary

The revolution of transportation will impact the overall energy cycle directly and indirectly in the future, including the fossil fuels which are currently mainly used for ICEV and power generation in electricity sector. This study focuses on the potential utilization of EVs in the Indonesian power grid, especially for peak load shaving and cost of reduction.

As a developing country, the demand for electricity in Indonesia increases, leading to several problems including those regarding peak time electricity growth. The potential of EV utilization for load leveling and frequency regulation in Indonesia is briefly described in this study. Massive EV adoption and participation in V2G can be considered as a potential method for achieving a high quality of electricity in the country. The results show that the peak supply from fossil fuels is effectively reduced by up to 2.81% (for coal) and 8.94% (for gas) in Case 5, i.e., EVs that stay home the entire day except on the weekends, as representative of commuter behavior in a metropolitan city. The driving pattern of Case 4 is one option, as commuting workers with EVs reduce the fossil generation supply especially gas fuel by approximately 2.8% (for coal) and 8.8% (for gas).

Power company gets the benefit of increasing the power consumption, owing to EVs charging in the night (off-peak period), and of reducing the cost of fossil fuels, which only peaks in certain periods. The calculation shows that when the V2G is used to partly substitute for the supply from gas, the power company can improve cost of generation on peak with V2G by approximately 26.5% in case 5 with a natural tariff.

As the share of renewable energy to the total electricity load is high, it is considered that the potential for frequency regulation by EVs will increase accordingly. Several challenges and barriers related to the utilization of EVs for grid ancillary services need to be analyzed and solved urgently, as the number of EVs is increasing sharply.

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Chapter 41
Techno-economic Analysis on Renewable Energy via Hydrogen from Macro and Micro Scope Views

Meng Chen, Tatsuya Ookubo, Kei Hasegawa, Manabu Ihara, Takuya Oda, and Koji Tokimatsu

Abstract Since 2012, the Japanese government has widely adopted variable renewable energy (VRE), especially photovoltaics (PVs), as a result of the Feed-In-Tariff (FIT) system. However, energy storage technologies must reduce their burden on the electric power grid to make best-use of intermittent renewable power sources. Power-to-Gas (P2G), which converts surplus power from VRE to hydrogen, is a promising candidate for large-scale and long-term energy storage technology. We utilized analytical models based on actual data from micro-side research and simulation results from macro-side one. We assume that the system either uses a combination of electrolysis cells (ECs) and hydrogen fuel cells (FCs), or ECs and hydrogen co-firing using surplus power from PVs, and will be introduced around 2030 on both sides of the micro (building) and macro (power district area). On the macro side, we investigated power mix by a power planning model. We found that hydrogen fuel cells have great potential to increase local utilization of surplus power. On the micro side, we applied a cost evaluation model consisting of ECs, FCs, hydrogen storage, and PVs, with surplus power selling price as a given parameter. The model shows that total costs are lower when hydrogen is used. Additionally, when electricity selling price is volatile depending on power demand, the model predicts FC capacity expansion. We conclude that P2G has both cost competitiveness and environmental benefit, and that the combination of solar power and hydrogen is a promising technology which expands PV capacity beyond limits without combination.

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Keywords Hydrogen · FC (fuel cell) · EC (electrolysis cell) · Techno-economic analysis · Variable renewable energy (VRE) · Power to gas (P2G) · Photovoltaic (PV)

41.1 Introduction

Variable renewable energy (VRE) such as photovoltaic (PV) power has been rapidly introduced to Japan since 2012 thanks to the Feed-In-Tariff (FIT) system. However, due to the expansion of VRE, it is expected that growing surplus power from solar power may outpace the grid's power adjustment ability. To achieve a low carbon society, it is essential to expand VRE capacity beyond the current stabilized power supply system via energy storage (using batteries or hydrogen) or peak shaving.

Hydrogen-based energy storage technology is attracting attention because it offers more scale and longevity compared to batteries. Hydrogen can be used as a secondary energy source in mobile applications, as well as other applications such as hydrogen co-firing in gas fired power. In order to clarify the possibilities and challenges of hydrogen energy, we undertook a techno-economic assessment of hydrogen in both macro (i.e. co-firing in a power mix) and micro (i.e., P2G in a building with EC, FC, storage, and PV) views.

We have significant advances from previous research, e.g. The International Renewable Energy Agency's review report on hydrogen (International Renewable Energy Agency (IRENA) 2018). In Japan, Komiyama et al. (2014) wrote a review of the optimal power supply for hydrogen storage from surplus power under strict constraints on CO_2 emission. However, they targeted mainly wind power generation in Hokkaido, where wind resources are abundant. Aziz et al. (2017) developed an optimal power planning model enabling techno-economic analysis on hydrogen in both production and storage from surplus VRE in a power mix. However, they did not use actual PV data and instead use an estimate based on aggregated solar radiation data from the Japan Meteorological Agency. Additionally, as their focus was on power mix, they did not consider distributed energy including consumer-side hydrogen technologies.

These previous researches are either focused on single technology system operation (micro side) or on energy mixing but simplified calculations by using the estimated value of specific technologies (macro side). Thus, it is essential to analyze P2G technology from both macro and micro views, using actual data and establishing analysis models suitable for different implementation sizes and component technologies.

We conducted a study assuming an introduction date of 2030 of P2G technology from both macro and micro views. We used the following data: surplus power from solar power generation, EC, hydrogen tank, hydrogen FC (micro side, building level), co-fire (macro side, area level), and power demand as shown in Fig. 41.1. Sections 41.2 and 41.3 covers the macro and micro views, respectively. Moreover, we show the interlinking research between macro and micro sides in Sect. 41.4.

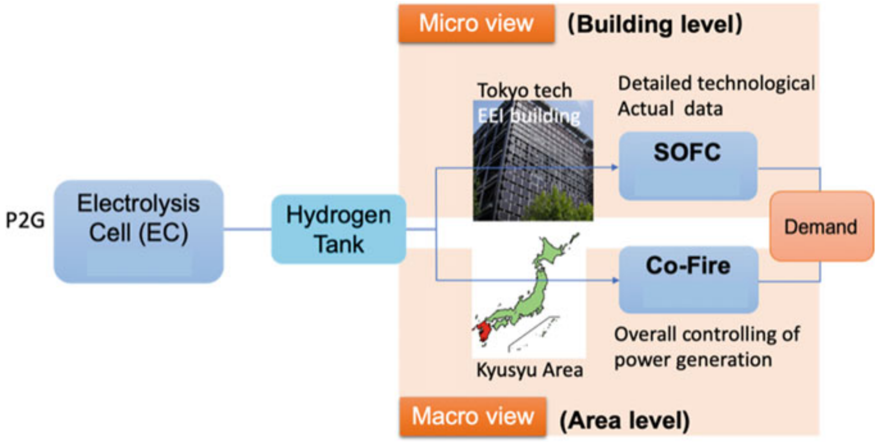


Fig. 41.1 The scope of this study

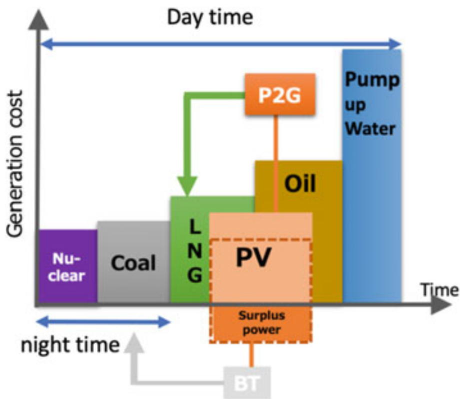
41.2 Macro Perspective

41.2.1 Methodology

The macro view analysis is based on previously developed model by Aziz et al. (2017). It is an optimal power planning model covering Kyushu area, assuming a system that produces and stores hydrogen from surplus power, in combination with thermal power plants. We expanded the power planning model to include hydrogen production equipment and storage tanks. Surplus power generation and power mix were analyzed using the power mix model, shown in Fig. 41.2.

The vertical axis represents the cost of various energy sources while the horizontal axis represents the hourly time of day. Low-cost nuclear and coal power sources are

Fig. 41.2 The power operation planning model



used both day and night whenever electricity price is low, and other energy sources such as natural gas, PV, oil, and hydro power are added only during the day time. From this analysis, we concluded that from the perspective of solving the difficulty of solar power expansion, P2G technology is beneficial. Because hydrogen can be generated (using PVs and ECs) and consumed (using hydrogen co-firing) in different place simultaneously, while batteries can only either charge or discharge, P2G technology offers an advantage since it can use surplus power during the day time as well (when electricity prices are higher). In this way, P2G enables communities to utilize zero-cost surplus power.

41.3 Result

To analyze the power mixing in Kyushu area and the characteristic of surplus power generation. Figure 41.3 models annual load duration curve in hourly basis for generation and surplus power in the Kyushu area. The horizontal axis represents larger-order of surplus power from left to right (L-shaped red curve; right vertical axis). The area graphs (blue in negative while the others such as gray in the left vertical axis) represents the amount of power generated by various energy sources.

Result shows that the time duration of surplus power generation is around 800 h/year (at a point of time to drop off zero in the red curve though actual number is higher than we expected), while the surplus power remains stable at around 300 kWh for 600 h, and 100 h afterwards, implying marginally balancing between the surplus power and demand changes. From Fig. 41.3, we conclude that as PV power increases in the future, surplus power's amount and duration will also greatly increase.

Figure 41.3 also indicates that we cannot rely on pumping hydro as a reliable energy source under various mixed renewable energies. When surplus power remains at 300 kWh, no power change is observed except from pumping hydro. This indicates that pumping hydro takes on the main role of power adjustment at 300 kWh. However,

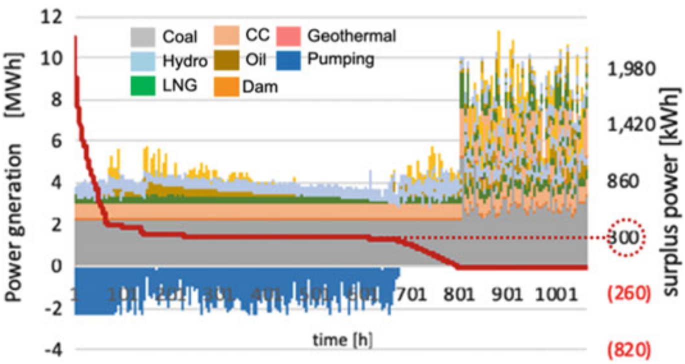


Fig. 41.3 The surplus power curve (red line, right axis) and power generation (area, left axis)

expansion of pumping hydro is limited by geographical conditions as pumping facilities can only be built on a large scale, their physical distance is typically to some extent away from other renewable energy sources unable to contribute to the power adjustment. Furthermore, when pumping hydro adjustment reaches its limit (left side of Fig. 41.3) surplus power disenables to adjust conventional power.

Our investigations in how to utilize this surplus power, focusing on distributed energy including hydrogen fuel cells as a solution.

41.4 Micro Perspective

41.4.1 Methodology

From the micro side, we used a P2G cost evaluation model, developed by Okubo et al. (Okubo et al. 2018), in a distributed energy system using PVs and hydrogen technology (the *technology system* hereafter). The model uses measured power demand and generation data from our Institute campus, and assumes an introduction year of 2030 for P2G technology, using ECs, FCs, and PV-sourced surplus power. The model also assumes a significant PV usage by 2030, backed by expected technical progress by that year.

Power market prices is important to apply this model in the real world. To this end, Apurba Sakti et al. conducted a techno-economic analysis on enhanced representations of lithium-ion batteries in power systems models and their effect on the valuation of energy arbitrage applications (Sakti et al. 2017). However, no research considers the power market in Japan using hydrogen energy storage technologies. Thus, we built an electricity selling model incorporating hydrogen energy and analyzed the operation of the technology system by using the volatile power price parametrically. Caveating that in this setting, we excluded either specific and non-existing schemes for supporting renewable powers nor extra crediting and funding mechanisms.

Selling model

Figure 41.4 shows the technology system model. In the P2G model (developed by Okubo et al. (Okubo et al. 2018), dark blue) PV, EC (including compressor), hydrogen tank, and FC determine the technology system's operation. If the amount of PV power supply exceeds demand, hydrogen is produced by EC electrolyzing the surplus power and stored in a high-pressure hydrogen tank. At this time, when the capacities of the EC and the hydrogen tank are insufficient, output control of surplus power is operated. If the PV power supply is less than the demand, the FC generates power using hydrogen to meet the power demand. If there is a shortage of power generated by the FC, then the system will purchase from grid power (Grid).

On the other hand, in the power selling model (developed by ours, in light orange), the selling time of surplus power is set (cf. the next subsection). The model assumes that whenever electricity can be sold, the technology system always sells

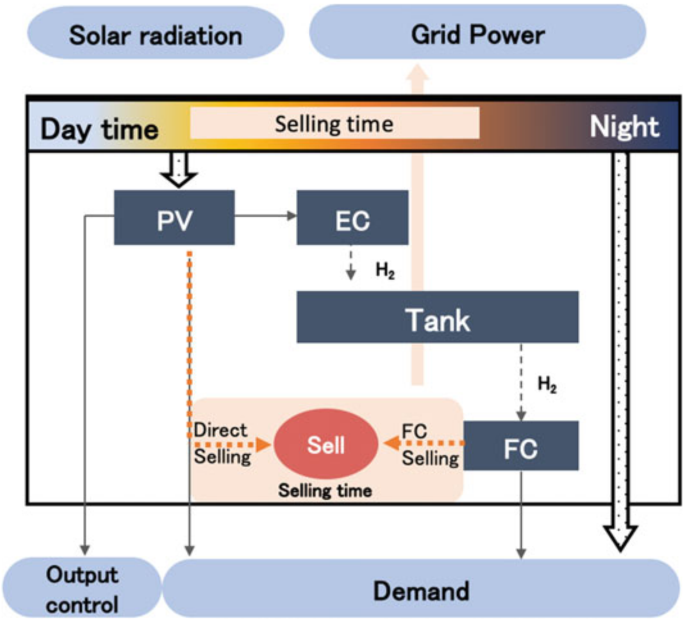


Fig. 41.4 The power selling model

FC-generated power to the grid. "FC selling" is defined as selling electricity from stored hydrogen power in FCs, and "direct selling" is defined as selling electricity from surplus power in PVs.

Selling time

Based on the curves of power supply and demand, with data sourced from the Tokyo Electric Power Company (TEPCO) [Past electricity usage data. TEPCO (2016, 2017)], we set the selling time shown in Fig. 41.5a. On the demand side shown in Fig. 41.5b, we used data from the EEI building in our Institute and determined the operational data of the technology system based on selling time. The proportion of PV in the future power supply configuration was set to 30%. It was also assumed that 30% of the power demand would be covered by PV and the rest would be covered by base-load power sources such as thermal power generation. Figure 41.5a shows a simplified power supply and demand curve for a 24-hour period by TEPCO. The base-load power generation must keep stable output in time periods during when the PV power supply capacity is lower than the power demand in selling time.

Technology system operation

By setting the selling time, we determined the technology system's operation on the demand side in a 24-hour period, as shown in Fig. 41.5b. During selling time, the power mix includes PV supply, power generation from FCs, direct selling, and FC selling. It is assumed that FC selling occurs whenever feasible. During non-selling

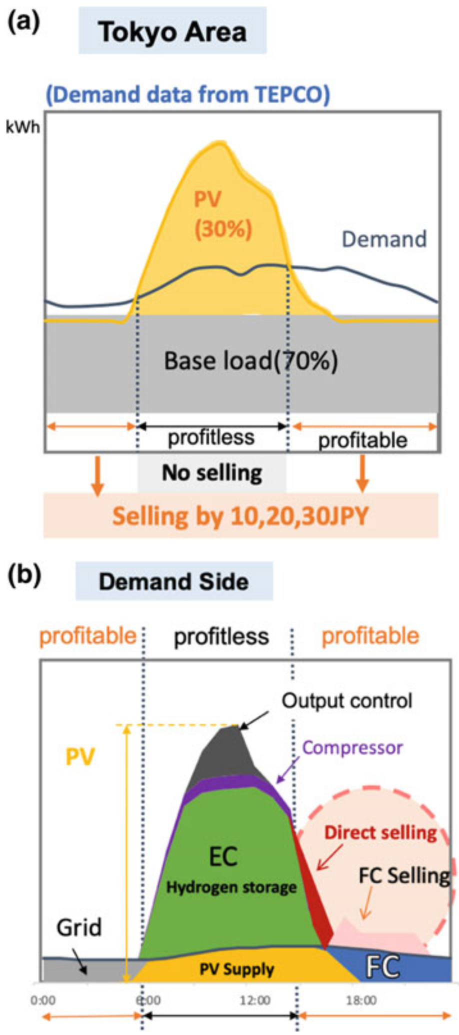


Fig. 41.5 Image of power supply in one day **a** Tokyo area (the upper image) **b** Demand side (the lower image)

time, the power configuration includes PV supply, hydrogen production from ECs, and PV output control.

Cost calculation

In this study, the combined cost of annual system cost and power sales revenue was used as the evaluation index. We present the calculation method below:

(1) **System cost**:

System cost is the total amount of initial cost and running cost. The calculation method of initial cost described as below:

(2) **Initial cost**:

a. *Introduction cost* as the product of unit price and each technology's capacity.
b. *Annual Introduction cost* is introduction cost divided by lifetime (measured in years).
c. *Initial costs* are the total sum of each technology's annual introduction cost.

(3) **Running cost**:

a. *Annual power consumption* from the operation of the technology system determined by the capacity of each technology.
b. *Running cost* is the product power purchase price and annual power consumption.

Technical parameters including unit price, lifetime, efficiency, etc. of each technology were set as shown in Table 41.1. In order to carry out the analysis while taking into consideration the future performance improvement of each technology, we estimated what each technology's performance in 2030 would be based on various references [Japan Science and Technology Agency Center low carbon society strategy (2016, 2017); Fuel Cells and Hydrogen Joint Undertaking (2014); Keizai (2017); International Energy Agency (2015); United States Department of Energy (2009); Tokyo Electric Power Company (2009)]. In this estimation, cost reduction by technological progress and learning by doing are taken into consideration. It is assumed that PV is a single crystal silicon type, EC is an alkali type, FC is a solid oxide type, and the hydrogen tank can handle 40 MPa compressed hydrogen.

41.4.2 Result

To clarify the cost composition of this model, we calculated total and detailed cost for 5 different patterns. Figure 41.6 shows the total cost and its breakdown in five different scenarios including 10JPY, 20JPY, and 30JPY in power grid price (Grid in grey bar graph), and Non-H2. The horizontal axis represents each scenario's relative cost to Grid (set at 1.0 wherein all electricity demand is satisfied by grid power). This is followed by the Non-H2 case (using PV power generation without storing surplus power) and then the selling power cases where demand is fixed regardless of the selling price (with selling power to the grid priced at 10JPY, 20JPY, and 30JPY, while purchasing power from the grid priced at a fixed in 21JPY). The bars in the graph represent relative cost for values >0, and amount sold for values <0. The red dotted line represents *total cost*, defined as annual system cost minus power selling revenue.

Comparing the scenarios of the selling prices of 20 JPY and 30 JPY with the case of Non-H2, the total cost is lower in the 20 JPY and 30 JPY scenarios. In these scenarios, although the technology system cost is high, the selling income is also high, in particular, power sold from FC accounted for the majority of the revenue.

Table 41.1 Device performance and electricity purchase price

Device	Parameter	Unit	Future value	References
PV	Unit price	JPY/kW	70,000	Japan Science and Technology Agency Center low carbon society strategy (2017)
	Lifetime	Year	30	Japan Science and Technology Agency Center low carbon society strategy (2017)
EC	Unit price	JPY/kW	70,000	Fuel Cells and Hydrogen Joint Undertaking (2014)
	Lifetime	Year	10	Fuel Cells and Hydrogen Joint Undertaking (2014)
	Efficiency	%	80	Fuel Cells and Hydrogen Joint Undertaking (2014)
FC	Unit price	JPY/kW	105,000	Japan Science and Technology Agency Center low carbon society strategy (2016)
	Lifetime	Year	20	Japan Science and Technology Agency Center low carbon society strategy (2016)
	Efficiency	%	65	Japan Science and Technology Agency Center low carbon society strategy (2016)
Tank	Unit price	JPY/L	5000	Keizai (2017)
	Lifetime	Year	20	International Energy Agency (2015)
Compressor	Unit price	JPY/ (Nm3/h)	200,000	Keizai (2017)
	Lifetime	Year	20	International Energy Agency (2015)
	Power consumption	kWh/kgH2	4	United States Department of Energy (2009)
Grid	Unit price	JPY/kWh	21	Tokyo Electric Power Company (2015)

Thus, when selling price is equal to or higher than the purchase price of electricity, hydrogen utilization technology is cost-competitive.

For each scenario, we calculated CO_2 emissions using an emission factor of 0.475 kg CO_2/L based on TEPCO 2017 (Electricity Rates and Rate Systems http://www.tepco.co.jp/en/corpinfo/illustrated/charge/overall-rates-e.html), and represent them proportionally to grid power CO_2 emissions, which is set at 100% (gray color). PV installation reduced CO_2 emissions by approximately 50%. CO_2 emissions were the lowest in the 10JPY scenario at 15.2%. This implies that CO_2 emissions can be reduced by up to 85% by using a hydrogen storage technology system.

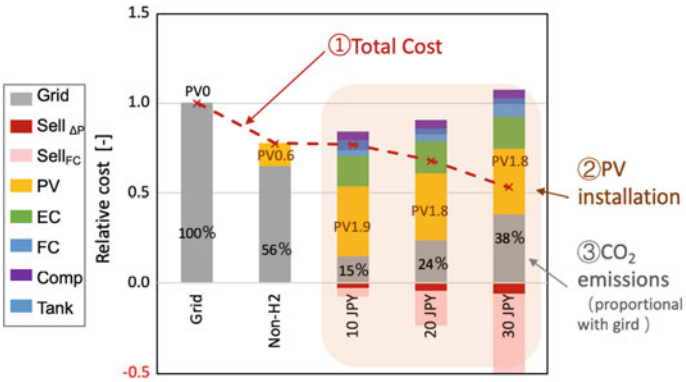


Fig. 41.6 Total cost and details of scenarios

41.5 Macro and Micro Perspectives

The above contents analyze the role of renewable use of hydrogen from micro and macro viewpoints. Combining these two views, we developed a grid-coordinated distributed smart energy system realistically for hydrogen technology usage in 2030 wherein fully deregulated power market. We use volatized selling price here instead of fixed price and redefined the selling time in the Sect. 41.3.

41.5.1 Methodology

The *actual demand* (dotted yellow line) is defined as the amount of demand without PV supply. Based on actual demand, we redefined the selling time shown in Fig. 41.7. We also revised the model from using a fixed price to using a volatile price. We calculated the volatile price based on historical actual demand using the electricity price curve. For simplicity, we ignored the grid-based adjustment cost by setting the annual minimum demand on the grid to the actual annual minimum demand of TEPCO in 2016, (the minimum power generation value on 2016, means that in this amount, it doesn't require gird adjustment control) (Fig. 41.7, orange line).

Figure 41.8 shows fuel cost lines for the Kyushu (left side) and Tokyo (right side) areas. The Kyushu fuel cost line is sourced from (Aziz et al. 2017), which is a linear regression of Kyushu Electric Power Company's (Kyushu Power Co.'s) fuel cost versus demand (Aziz et al. 2017). We created the Tokyo fuel cost curve for the TEPCO area as described below.

The fuel cost line in Fig. 41.8 shows the cost range of Kyushu Power Co. is 2~10JPY. We used TEPCO's actual minimum and maximum demand from 2016–2017 and assumed that TEPCO's maximum and minimum fuel costs are the same as

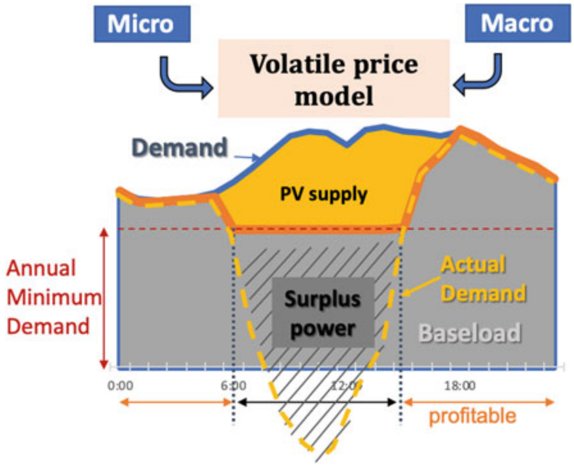


Fig. 41.7 The volatile price model

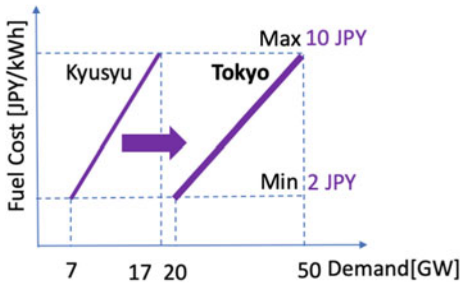


Fig. 41.8 The method of fuel cost curve in accordance with demand capacity

Kyushu Power Co.'s because the equipment used by both companies has the same power generation efficiency at peak and minimum load.

By substituting volatile prices for fixed prices in the micro-view electricity selling model presented in Sect. 41.3, we calculated the *demand-based hourly volatile price*, which is the sum of fuel cost, capital cost, and power company profit (Fig. 41.9).

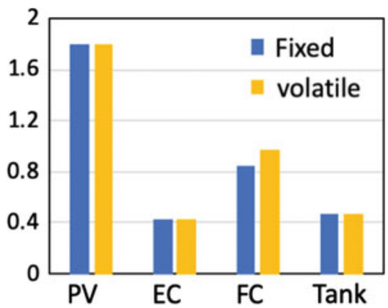


Fig. 41.9 Installation ratio of P2G device

Using this updated model, we optimized the system's total cost. The installation rate of EC, FC, and hydrogen tank were optimized at a PV installation rate of 1.8, which balances purchase and sales amounts. Although the installation rates of EC and Tank are almost the same between fixed and various models at minimum cost, the installation rate of FC increases. Our explanation for this is that when fixed prices are changed to volatile ones, FC plays a role in adjusting variable cost. This implies FC installation expansion is required to mitigate demand fluctuations in volatile price.

41.5.2 Future Consideration

The daily PV supply and power demand inevitably depend on weather conditions and other factors. Therefore, analyzing FC selling methods that can respond to these external factors is a logical next step. The following two FC selling methods should be considered.

1. Instead of selling at the full capacity, we should set a sales-volume ratio; i.e. selling at a high ratio in high prices, selling in a controlled manner in moderate prices, and not selling in low prices.
2. Since the shape of the price fluctuation curve doesn't change significantly daily, we should simulate FC sales accordingly. Specifically, sets sales to be suppressed when prices rise and to be sold in large quantities when prices fall.

41.6 Summary

We evaluated a hydrogen energy technology system from both macro and micro views. It is assumed that the technology system, which includes PV, EC and FC or hydrogen co-firing, will be introduced around 2030 on both micro (building) and macro (power district) levels.

On the macro side, power mix sourced from various energy technologies was investigated. We found that hydrogen fuel cells have great potential to increase the utilization of surplus power locally. On the micro side, a renewable energy system using hydrogen storage technology considering power sold by FCs was created. After evaluating this system, we clarified that incorporating the hydrogen system decreases costs. Furthermore, after substituting consumer demand-based volatile price for fixed price in the model, it became clear that FC installation expansion will be necessary.

We conclude that the hydrogen-based technology system has demonstrated cost merit and environmental benefit, and that solar power could see widespread usage in the future when combined with hydrogen storage.

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Chapter 42
Dynamic Simulation of Woody Biomass Co-generation System Considering Time-Varying Heat Demand: A Japanese Community Bathhouse Case Study

Noriaki Nakatsuka, Yusuke Kishita, and Fumiteru Akamatsu

Abstract Since the implementation of the feed-in-tariff scheme in Japan in 2012, the number of Japanese power generation plants using woody biomass has been increasing. In order to maximize the amount of usable energy extracted from woody biomass, however, it is necessary to use the generated heat in a way that meets heat demand fluctuations. This paper proposes a model that enables the dynamic simulation of a woody biomass co-generation system, taking into account the balance of heat demand and supply. The model is developed using life cycle simulation to evaluate and compare different configurations of energy conversion systems from both economic and environmental viewpoints. A case study involving a community bathhouse in Nara, Japan was conducted using two scenarios: one in which only heat is supplied using conventional heavy oil, and a second in which both heat and electricity are supplied by introducing gasification combined heat and power (CHP) equipment using wood resources. A comparison of the two scenarios showed that CO_2 emissions in the CHP scenario were 190% lower than those in the heavy oil scenario. Moreover, the cost of the CHP scenario was 23% lower than that of the heavy oil scenario due to electricity sales based on the feed-in-tariff scheme.

Keywords Woody biomass · Dynamic simulation · Heat demand fluctuation · Co-generation · Economic and environmental analysis

42.1 Introduction

In recent years, a rapid transition to a low-carbon society has been underway in response to environmental problems such as global warming that have arisen from the industrial development of human society. The use of renewable energy is one of the primary elements of this transition. Until now, forest land residues, that is,

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unused woody biomass, have been used sparingly as an energy source due to high transport costs. However, they offer a highly promising energy resource, particularly in mountainous areas (Meier et al. 2019; Rosillo-Calle 2000; Bracmort 2016). To promote the utilization of unused biomass, combined heat and power (CHP) systems have been used to generate both electricity and heat from woody biomass. A gasification CHP system is considered to be one of the more effective technologies because of its high energy conversion efficiency in small-scale applications (Yoshikawa and Moritsuka 2006; Heidenreich and Foscolo 2015a, b; Rovas and Zabaniotou 2015; Hasler and Nussbaumer 2016; Molino et al. 2016; Park et al. 2018).

Although there are a number of methods to evaluate the environmental and economic performance of woody biomass utilization, there remains the challenge of designing a sustainable configuration of energy conversion systems (e.g., CHP system) for woody biomass that takes into account both the daily fluctuations in heat demand and the effects of long-term social changes. The purpose of this study is to propose a method to conduct dynamic simulations of woody biomass energy conversion systems considering time-varying heat demand. To enable such a dynamic simulation, an energy conversion system is modeled as a sequence of processes by means of life cycle simulation (LCS) (Umeda et al. 2000). LCS was originally designed to simulate product life cycle flows using discrete event simulation. This approach enables the quantitative evaluation of a product life cycle from both environmental and economic viewpoints. In this paper, annual cost and annual CO_2 emissions are used as indicators of economic and environmental performance. Alternative scenarios are created to allow a comparative analysis of different configurations of energy conversion systems. The case study presented here centers on a Japanese hot bath facility in Gojo City, Nara Prefecture. Given the location of the subject facility, the availability of a woody biomass supply from the surrounding area can be easily assumed. Moreover, a certain amount of demand for heat and power exists.

42.2 Literature Review

Considerable research on small-scale biomass CHP systems has been conducted, primarily from a techno-economic point of view. For example, von Doderer and Kleynhans (2014) conducted a life cycle assessment and showed that the most viable and sustainable bioenergy system for the Worcester biomass procurement area region is a lignocellulosic bioenergy system composed of a feller buncher for harvesting, a forwarder for biomass extraction, mobile comminution at the roadside, secondary transport in truck-container-trailer combinations, and an integrated gasification system for conversion into electricity. Cleary et al. (2015) estimated the nominal electricity generation and greenhouse gas (GHG) mitigation costs of using harvest residue from a hardwood forest in Ontario, Canada to fuel (1) a small-scale (250 kWe) CHP woodchip gasification unit and (2) a large-scale (211 MWe) coal-fired generating station retrofitted to combust wood pellets. Under favorable operational and regulatory conditions, the generation costs were found to be similar.

Patel et al. (2016) reviewed relevant studies not only from a technological viewpoint but from a life cycle assessment viewpoint and concluded that environmental studies of biomass gasification have proven the potential of reducing GHG emissions, but that there is a need for more comprehensive life cycle assessments, taking into account all environmental impact categories. Lu and Hanandeh (2017) conducted a comparative life cycle assessment and life cycle costing analysis to evaluate six options—woodchip gasification for power generation, wood pellet gasification in a CHP plant, wood pellet combustion for domestic water and space heating, pyrolysis for power generation, pyrolysis with bio-oil upgrading to transportation fuels, and ethanol production for a transportation fuel mix—and showed that all options except for ethanol production are GHG emission negative and that woodchip gasification performed best in all environmental impact categories and had the lowest life cycle cost. Yang et al. (2017) conducted a life cycle assessment to evaluate the optimum scale of a combined cooling, heating, and power system based on biomass gasification, and showed that biomass cost, the cost of the energy supply, environmental impact, and energy consumption all first decrease as scale is gradually increased, then increase as scale continues to increase, and that comprehensive performance is optimal when the scale of the system is approximately 5 MW. You et al. (2017) conducted a life cycle assessment and cost-benefit analysis to compare the global warming impact and economic feasibility (net present value and levelized cost of electricity) of an alternative oil-palm biomass gasification system with the environmental impact and economic viability of current practices in rural Indonesia (diesel generator for village use and biomass boiler combustion for mill use). Sensitivity analysis showed that the capital cost of the gasification system and its overall electrical efficiency had the most significant effects on net present value. Li et al. (2018) carried out a life-cycle assessment using a multi-criteria optimization for a biomass gasification-integrated combined cooling, heating, and power system. Primary energy savings, total cost savings, and the reduction in CO_2 emissions served as the criteria. The overall-performance criterion was determined by applying TOPSIS (Technique for Order of Preference by Similarity to Ideal Solutions). Results showed that the overall-performance criterion was maximized when the nominal electric output was 1572.8 kW, the biomass feedstock type was wood pellet, and the operation strategy was to follow the electric load. Ogorure et al. (2018) conducted an energy, exergy, environmental, and economic analysis of a proposed agricultural waste-to-energy integrated multi-generation power plant. A combination of anaerobic digestion and gasification was used to convert the agro-wastes to synthetic gas, which was subsequently converted to electrical energy and refrigeration in an integrated multi-generation plant composed of a solid oxide fuel cell stack, gas turbine, steam turbine, organic Rankine, and absorption refrigeration cycles. Results indicated a life cycle cost of \$3.753 million, a breakeven point of 7.5 years, a unit energy cost of \$0.0109 per kWh, and specific CO_2 emissions of 141.2 kg/MWh. Yang et al. (2018) conducted a hybrid life-cycle assessment of the energy consumption and GHG emissions of a typical biomass gasification power plant in China and showed that the non-renewable energy cost and GHG emission intensity of the biomass gasification system were 0.163 MJ/MJ and 0.137 kg CO_2-eq/MJ, respectively, which reaffirmed the advantages of such a system over coal-fired power plants in terms of clean energy and environmental impact. Jeswani et al. (2019) conducted a life cycle assessment and life cycle costing to evaluate the life cycle environmental and economic sustainability of poultry litter gasification and showed that energy from this system had lower impacts than the fossil-fuel alternatives in 14 out of 16 impact categories, and that even without subsidies, the cost of generating heat and electricity from poultry litter was 37–66% lower than the cost resulting from the use of fossil fuels. However, it was concluded that without subsidies, the system would not be economically viable, as the payback period would increase to 25 years. Wang et al. (2019) conducted life cycle environmental and techno-economic assessments within a boundary ranging from agriculture residues collection and transportation to energy conversion and final use of bioenergy products and showed that direct-combustion power generation, gasification power generation, and briquette fuel are the most sustainable technologies in both an environmental priority situation and an economic priority situation based on their integrated-dimensions performance.

As described above, there have been multiple studies involving economic and environmental assessments of woody biomass energy use based on energy balance. There are, however, few approaches that include a dynamic simulation that takes into account daily fluctuations in energy demand to evaluate the annual cost and environmental load associated with a woody biomass gasification CHP system. It should be noted that while Li et al. (2018) considered hourly energy demand to find the optimal operation strategies for a CHP system, a comparative analysis of different system configurations has not yet been undertaken. Furthermore, there are very few case studies focused on Japan, despite the fact that forest areas account for 67% of the country's surface area, which suggests a huge potential for woody biomass utilization.

42.3 Modeling Energy Conversion Systems for Woody Biomass

42.3.1 Approach

We evaluate the annual cost and annual CO_2 emissions of energy conversion systems for woody biomass by modeling each facility process (e.g., chipping, pelletizing, and gasification). The modeling approach uses the abovementioned LCS (Umeda et al. 2000), which is a system that simulates a product life cycle flow based on the input-output relation between two processes throughout the life cycle. A key characteristic of LCS is its capability to describe any type of process by defining the procedure (i.e., the calculation formula connecting input and output parameters) of each process. In this study, we apply LCS to the material and energy flow of woody biomass, rather than product life cycle flow, taking into account dynamic changes in heat demand.

42.3.2 Model for Calculating Annual Cost

We calculate *Ac*(*t*), the annual cost of a facility in year *t,* with the time step of the simulation (cutting width) set to Δt and the number of time steps set to n (= 1/Δt) as follows:

$$\mathrm{Ac(t)} = \sum_{\mathrm{i=0}}^{\mathrm{n}} (\mathrm{Fc(t, i)} + \mathrm{Dc(t, i)} + \mathrm{Mc(t, i)} + \mathrm{Ec(t, i)} - \mathrm{Es(t, i)}) \tag{42.1}$$

where *Fc*(*t*, *i*) is fuel cost, *Dc*(*t*, *i*) is depreciation cost, *Mc*(*t*, *i*) is maintenance cost, *Ec*(*t*, *i*) is electricity cost, and *Es*(*t*, *i*) is power consumption in the *i*th stage of year *t*.

42.3.3 Model for Calculating Annual CO_2 Emissions

The annual CO_2 emissions of the facility, *Ae*(*t*), is calculated by the following equation:

$$\mathrm{Ae(t)} = \sum_{\mathrm{i=0}}^{\mathrm{n}} (\mathrm{Fe(t, i)} + \mathrm{Eu(t, i)} - \mathrm{Pg(t, i)}) \tag{42.2}$$

where *Fe*(*t*, *i*), represents CO_2 emissions from fossil fuel consumption, *Eu*(*t*, *i*) *is* CO_2 emissions when purchased power is generated, and *Pg*(*t*, *i*) is the reduction in CO_2 emissions when no power to sell is generated.

42.4 Case Study: Evaluation of Energy Conversion System for a Japanese Hot Bath

42.4.1 Description of the Scenarios

In this study, two scenarios—scenario A and scenario B—are assumed for the selection of an energy conversion system at a hot bath facility in Gojo City, Japan. In scenario A, heat is supplied by a heavy fuel boiler. In scenario B, a small gasification CHP system using woody biomass is used to meet the base load heat demand; the heat supply is produced by a woodchip boiler, with a heavy oil boiler as a backup heat source. A hot water tank serves as the thermal storage device. The simulated evaluation period is 1 year (2018); the time step is 1 h.

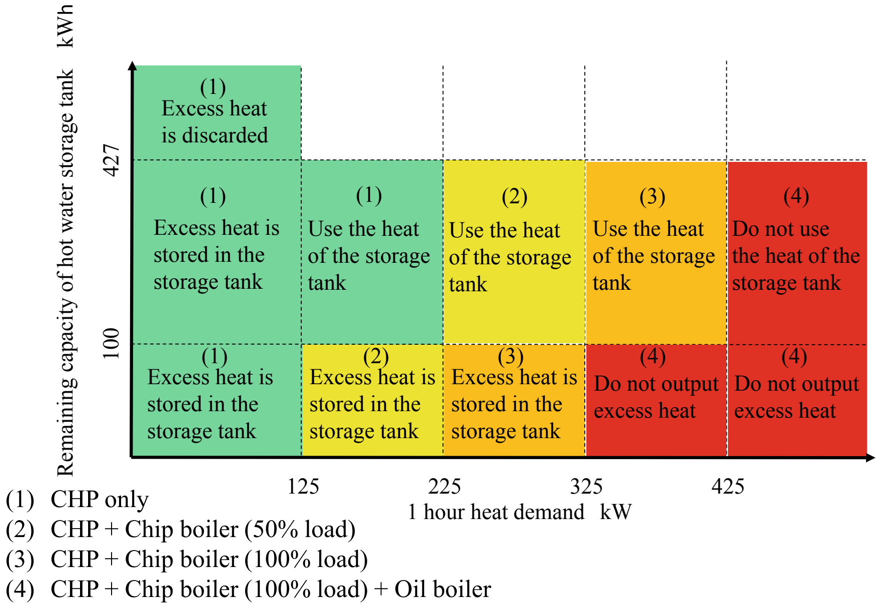

Fig. 42.1 Operation algorithm for thermal equipment

42.4.2 *Equipment Operation Management in the Two Scenarios*

In scenario A, it is assumed that the heat supply needed to meet fluctuating hourly heat demand is produced by injecting fuel at the appropriate rate into the heavy oil boiler. In scenario B, the CHP operates in a weekly start and stop (WSS) mode, from 8 am on Thursday to 8 pm on Monday. The chip boiler operates at either full "Stop," "50% load," or "100% load," as shown in Fig. 42.1.

A heavy oil boiler performs the appropriate partial load operation in the same manner as in Scenario A. The heat supply and the heat storage amount in the hot water tank are determined in each step, based on the chart in Fig. 42.1.

42.4.3 *Data*

To calculate the cost and CO_2 emissions of the energy conversion system at the hot bath facility, the necessary data were collected through a literature search, field surveys, etc. Table 42.1 shows the key values, including purchase price and installation costs, as well as the useful life of the various system components. The actual heat demand at the targeted hot bath facility for a 1-week period in early November 2018 was determined based on the consumption of heavy oil during that week. Figure 42.2

Table 42.1 Initial cost, setting cost, maintenance cost, and useful life of equipment

Item		Cost	Useful life	Notes
		Yen	Years	
Heavy oil boiler	Main unit	2,687,000	13	Estimate from HIRAKAWA
	Installation	700,000		
HOLZ125	Main unit	110,000,000	10	Interview to HolzEnergie
	Installation	0		
Wooden chip boiler	Main unit	36,700,000	13	Estimte from TOMOE-TECHNO
Basis of the machine room	Civil engineering	19,500,000	31	Estimte from TOMOE-TECHNO
Het supply system Piping, electric equipment	Main unit	7,960,000	13	Estimte from TOMOE-TECHNO
	Installation	52,020,000		Estimte from TOMOE-TECHNO

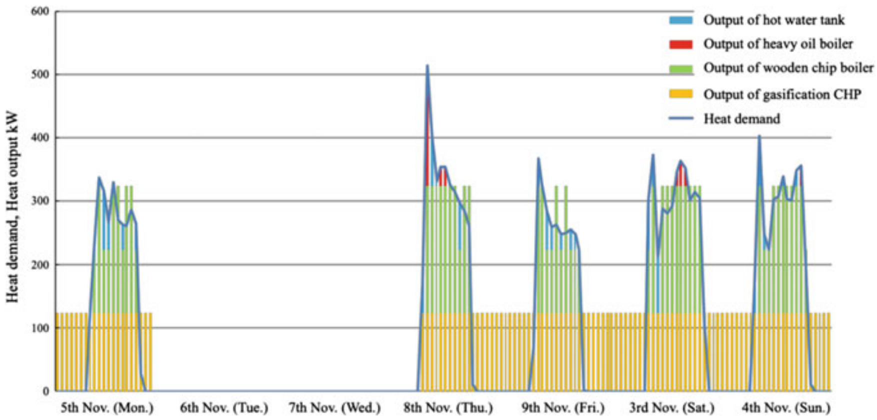

Fig. 42.2 Heat demand and heat output during a 1-week period in November 2018

shows the heat supply breakdown for scenario B based on the acquired heat demand data. In this study, to determine the 1-year heat demand, we assumed that the weekly heat demand for each month is the same trend shown in Fig. 42.2, and monthly heat demand data is acquired. The woodchip purchase cost was set at 14,300 yen/t based on an interview conducted at the Gojo City facility.

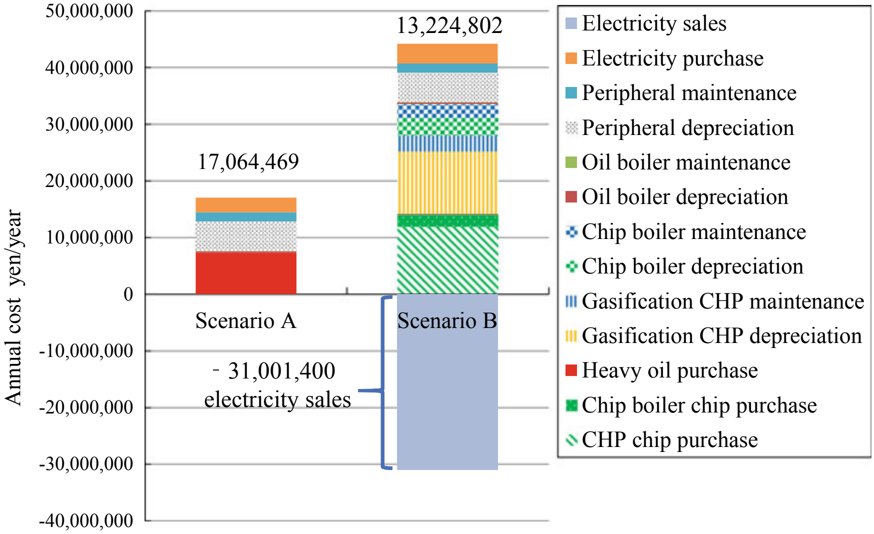

Fig. 42.3 Breakdown of annual cost for scenarios A and B

42.5 Results and Discussion

42.5.1 Annual Cost

Figure 42.3 shows the annual costs calculated for fiscal 2018. As can be seen here, the scenario A cost is 17,064,469 yen and the scenario B cost is 13,224,802 yen. The 3,839,667 yen difference represents a 23% lower cost for scenario B.

In scenario B, although the cost of introducing the woody biomass gasification CHP system and the purchase cost of woodchips dominate the annual cost, resulting electricity sales produce a significantly lower net annual cost relative to scenario A. The cost reduction ratio of scenario B (CHP scenario) in the present study (23%) is lower than that in the United Kingdom case (37–66%) (Jeswani et al. 2019), which is mainly due to the lack of subsidies for heat in Japan.

42.5.2 Annual CO_2 Emissions

Figure 42.4 shows the the annual CO_2 emissions calculated for fiscal 2018. As indicated, scenario A emissions are approximately 260 t/year, while scenario B emissions were approximately −230 t/year.

The difference in CO_2 emissions is thus 490 t/year. This difference is due in large part to the application of the carbon neutral concept to woodchip combustion; the size of the CO_2 reduction is based on the amount of power that a power company purchases from the CHP system.

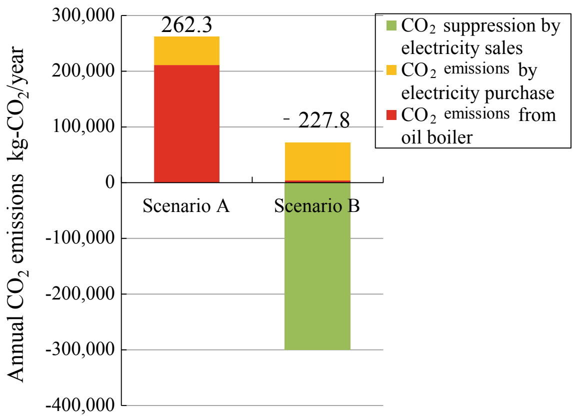

Fig. 42.4 Breakdown of annual CO_2 emissions

42.5.3 Sensitivity Analysis

A sensitivity analysis is conducted for annual cost and annual CO_2 emissions in both scenarios in order to further examine conditions for the sustainability of the woody biomass energy alternative. Detailed results are explained below.

Annual cost

Figure 42.5 shows the impact on annual cost when the indictated parameters are increased by 10% from their original values. As Fig. 42.5 indicates, electricity selling price, the power generation efficiency of CHP, woodchip price, and CHP depreciation cost all have at least a 5% effect on annual cost in scenario B, indicating that these parameters are critical to scenario B's economic advantage (i.e., cost savings).

Figure 42.6 shows the annual cost for both scenarios when the selling price of electricity varies from 0 to 120% of its original value. As indicated, the cost of

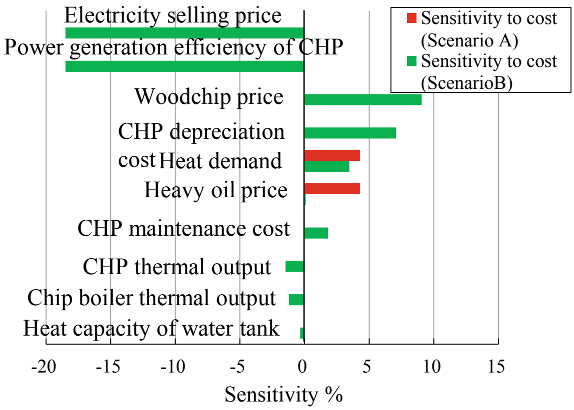

Fig. 42.5 Sensitivity of annual cost

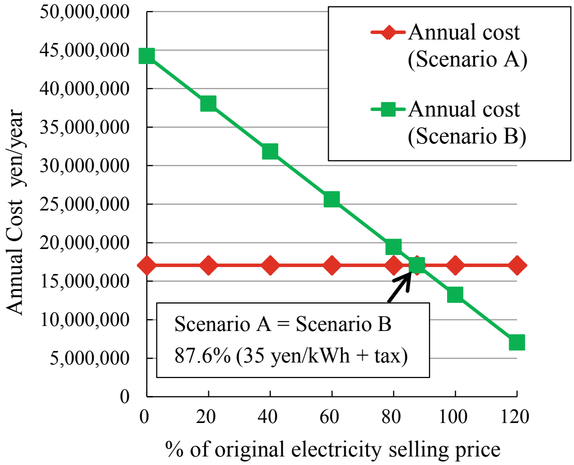

Fig. 42.6 Annual cost when varying the selling price of electricity

scenario A will be equal to that of scenario B when the selling price of electricity is approximately 88% (35 yen/kWh + tax) of the original 40 yen/kWh + tax value.

Figure 42.7 shows the total annual cost when varying woodchip price from 0 to 200% of its original value. As indicated, the annual cost of scenario A is equal to that of scenario B when the woodship price is approximately 130% (18 yen/kg) of its original 14.3 yen/kg value.

Figure 42.8 shows the influence of woodchip price and electricity selling price on the annual cost of the two scenarios. Note that the solid line indicates the condition in which the annual costs for the two scenarios are equal. As described here, the annual cost in the original condition for scenario B is slightly lower than that in scenario A. As a matter of economic sustainability, it is possible to raise the woodchip price by

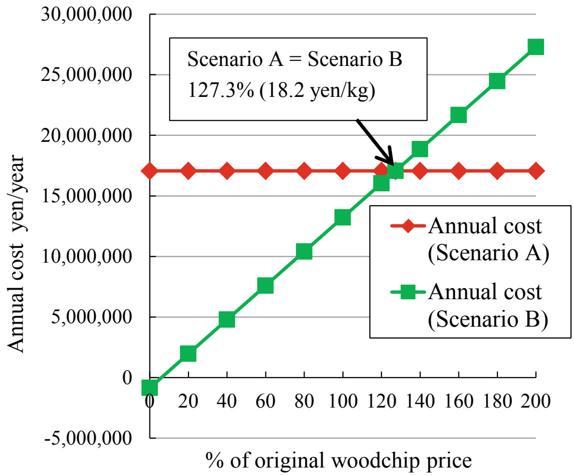

Fig. 42.7 Annual cost when varying the woodchip price

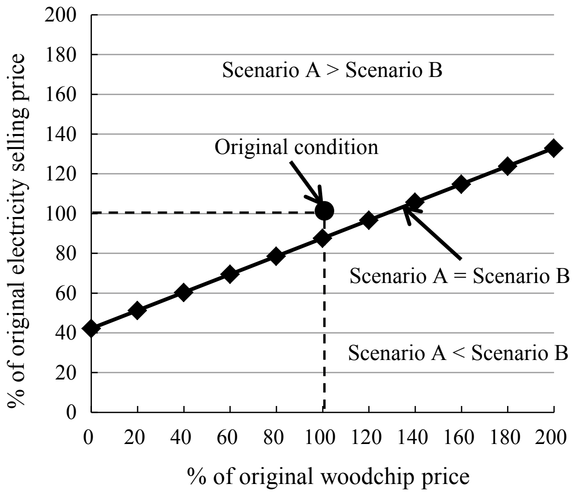

Fig. 42.8 Influence of woodchip price and electricity selling price

raising the selling price of electricity, which will increase the income of the forestry business operator.

Annual CO_2 emissions

Figure 42.9 shows the impact on CO_2 emissions when each of the relevant parameters is increased by 10% from its original value. As indicated in Fig. 42.9, power generation efficiency of CHP in scenario B and heat demand in scenario A have more than a 5% impact. Notably, heat demand in scenario A has a relatively strong effect on CO_2 emissions (8.1%), whereas, in scenario B, it has a relatively small effect (1.6%). Taken together, the results shown in Figs. 42.4 and 42.9 indicate that scenario B emits less CO_2 than scenario A regardless of any potential increase in heat demand.

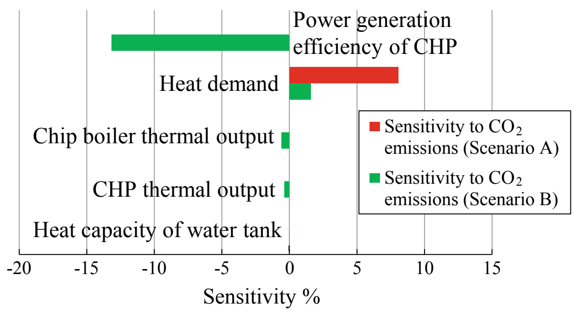

Fig. 42.9 Sensitivity of annual CO_2 emissions

42.6 Conclusion

In this paper, we proposed a model to analyze woody biomass energy conversion systems using life cycle simulation (LCS) (Umeda et al. 2000). The proposed model considers fluctuations in hourly heat demand and provides the means to assess the operation of the system and identify ways to improve its economic and environmental performance. In the hot bath case study, two scenarios were created to allow for a comparative analysis of different configurations of energy conversion systems. In scenario A, a heavy oil boiler was used to supply the required heat; in scenario B, a gasification CHP system using woody biomass was assumed. Results showed that, in scenario B, annual cost was lower by 23% and CO_2 emissions were lower by 190% relative to scenario A. Sensitivity analysis revealed that the selling price of electricity and the power generation efficiency of the CHP system are critical parameters in establishing the economic advantage of scenario B. As a matter of economic sustainability, it is possible to raise the woodchip price by raising the electricity selling price, which will increase the income of the forestry business operator providing the woodchips. It was found that annual CO_2 emissions were highly sensitive to the power generation efficiency of the CHP system in scenario B, and to heat demand in scenario A. As a focus for future research, integrating scenario analysis methods (e.g., Kishita et al. 2016) and the quantitative model proposed in this paper would be of significant value in helping system designers derive better designs and proper operational guidelines for energy conversion systems by taking into account both long-term social changes (e.g., oil prices and electricity selling prices in the Feed-in-Tariff system) and short-term (e.g., hourly) energy demand fluctuations. Modifying the timeline of the study (e.g., from 2019 to 2039), collecting more data to improve the modeling of biomass gasification CHP systems, and verifying the simulation results through experiments in real fields are also matters for future consideration.

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Chapter 43
A Feasibility Study of a Japanese Power to Gas Concept—A Case Study of Rokkasho Village

Yuji Mizuno, Yuki Ishimoto, and Shigeki Iida

Abstract Power to Gas is a concept of producing hydrogen from intermittent renewable energies. In this study, the authors investigate the feasibility of a Japanese Power to Gas concept. The authors focus on Rokkasho Village in Aomori Prefecture, Japan. The area has affluent renewable energy potential and already has a lot of wind turbines and photovoltaic panels. It also has very cold winter weather and large amount of fossil fuels are used for room and water heating. In order to reduce such fossil fuel usage and CO_2 emission in the area, the authors propose a fuel cell combined heat and power (CHP) system for cold area with local hydrogen supply chain, and analyze the feasibility of it. The energy and material balance, cost of hydrogen, and CO_2 emission reduction effects are studied. From the electricity and fossil fuel consumption data of public facilities in Rokkasho Village, appropriate fuel cell CHP facilities are selected and hydrogen demand of them are calculated. Hydrogen supply is calculated from wind speed and sun light intensity data of the Rokkasho Village, renewable energy capacity, and threshold of electricity supply usable for hydrogen production on renewable energy output. Hydrogen storage capacities are determined to balance the supply and demand. The CAPEX is calculated based on the equipment in the CHP system and OPEX is calculated from electricity cost and industrial water price. The reduction of CO_2 emission is calculated based on the amount of heat and electricity supply replaced with hydrogen CHP. The result indicates that 1. hydrogen production only from “excess” renewable energy is not economically feasible, 2. operation of electrolyzer can reduce the size of hydrogen production facilities and the cost of hydrogen, and 3. Hydrogen combined heat and power reduces more CO_2 than just supplying heat from hydrogen.

Keywords Renewable energy system · Power to gas · Renewable hydrogen · Combined heat and power · Fuel cell

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43.1 Introduction

Hydrogen is seen as a hopeful energy carrier to realize the low-carbon society. It produces only water when it is used in boilers, fuel cells, gas turbines, and so force. It can be produced from various feedstocks and methodology, especially, water electrolysis with renewable electricity. This means hydrogen can contribute to supply low-carbon energy source locally and storing uncontrollable renewable electricity.

"Power to Gas (PtoG)" (European Powertogas 2019) is an important concept about renewable hydrogen proposed by Germany. Here, "Power" means renewable electricity and "Gas" means hydrogen and hydrocarbon gases. The objective of Power to Gas is to balancing electricity supply and demand and to distribute renewable energy in gaseous form without building new electricity grid to the wider region in the country and sectors, such as transport and industry. Under the Power to Gas concept, unutilized renewable electricity generated by wind turbines in the north shore of Germany is transformed into hydrogen and distributed to the south via existing natural gas pipeline network.

There are many demonstration projects about producing hydrogen from renewable energy (Gahleitner 2013). In Japan, mainly New Energy and Industrial Technology Development Organization (NEDO) is funding several Japanese Power to Gas demonstration projects. Many techno-economic feasibility studies about them are also conducted (Walker et al. 2016; Kopp et al. 2017; Simonis and Newborough 2017; Gotz et al. 2016). For Japan, Shibata (2016) discussed the feasibility of Power to Gas in Japan from the multiple viewpoints.

The existing capacity and potential of renewable energies and local problems are different from area to area. In order to increase domestic renewable energy and hydrogen in Japan, proposing and evaluating Japanese Power to Gas concepts on each area's boundary conditions is important.

43.2 Objective and Approach

In this paper, the authors propose a Japanese Power to Gas concept and conduct techno-economic feasibility study about it. The authors take the following two approaches to meet the objective:

1. Proposing the concept by not just copying German concept, but by considering Japanese situation, such as existing energy infrastructure.
2. In the feasibility study, in order to apply the concept and evaluation method to other similar area, using open data and method.

43.3 A Japanese Power to Gas Concept

The model area of this concept is Rokkasho Village in Aomori Prefecture. The village locates in north east end of Honshu Island, Japan. As many cold and rural areas in Japan, fossil fuels, especially manually transported fuel oil is used for water and room heating in winter. Especially, Aomori Prefecture has the second largest fuel oil consumption in Japan (The Institute of Energy Economics 2007). Fuel oil is an imported fossil resource, so such energy supply is not sustainable. On the other hand, Rokkasho Village has great renewable energy potential and there are already a lot of wind turbines and photo voltaic panels. However, Japan has no nation-wide natural gas pipelines as Europe (Shibata 2016), so if renewable hydrogen is produced in Rokkasho Village and similar rural areas, it is not easy and cheap to transport to other areas.

Based on these situations, the authors propose "fuel cell combined heat and power system for cold area with local hydrogen supply chain" as a feasible Japanese Power to Gas concept. Part of heat and electricity demand in the area is supplied by fuel cells using locally produced renewable hydrogen. The hydrogen output from the electrolyzer is stored without additional compression (< 1.0 MPa) and distributed through the local hydrogen pipeline network using differential pressure. The system contributes to reduce CO_2 emission from water and room heating and the hydrogen supply cost is minimized because the transportation distance is minimized. Fuel expenditure is back to local renewable energy producers not to foreign countries. This concept is applicable to similar areas, which is cold, rural, and having rich renewable energies. This model can be realized around 2030, when renewable energies operated under Japanese FIT (Feed-in-Tariff) rules will be released to free electric power market. The target year of the feasibility study is 2030 and the authors used the data of 2016 for the study. (Table 43.1).

Table 43.1 Demand patterns

Pattern	Month	Ele. and fuel bill reference month
Winter	December–March	February
Winter–Spring Autumn–Winter	April, November	N/A
Autumn and Spring	May, October	April
Summer	July, August	August
Spring–Summer, Summer–Autumn	June, September	N/A

43.4 Methodology of Feasibility Study

In the feasibility study of the proposed PtoG concept, the size and number of fuel cells, electrolyzers, and hydrogen tanks, are determined through yearly electricity and material input and output simulation. Assumed the cost of facilities, renewable electricity, and water and based on them, levelized unit cost of hydrogen are calculated. The economic and environmental value of hydrogen is compared with that of equivalent combination of grid electricity and heat from conventional facilities.

Specific process of the study is as follows:

1. Making the consumers' yearly electricity and heat demand pattern.
2. Selecting fuel cells to install into the consumers and setting yearly operation pattern of them based on the electricity and heat demand pattern.
3. Based on the weather data and capacity of renewable energy facilities, assuming the power generation pattern.
4. Determining the hydrogen production pattern, by assuming the capacity of the electrolyzer and the electricity intake rules.
5. Assuming the capacity of hydrogen storage facility by hydrogen demand and supply pattern.
6. Calculating unit cost of hydrogen from the number and capacity of facilities and assumed electricity and water cost.
7. Evaluating the economic feasibility by comparing hydrogen cost with equivalent cost combination of grid electricity and heat from fossil fuel.
8. Evaluating CO_2 reduction from deduced grid electricity and fossil fuel consumption.

43.4.1 Step 1. Electricity and Heat Demand

The consumers of hydrogen in Rokkasho Village includes seven public facilities, 200 detached houses, and housing complex for 1,496 families. Public facilities include one city hall, one community center, two schools, one hospital, one heated pool facility, and one centralized kitchen for schools.

A year is represented by five seasonal patterns. Each pattern has hourly value of electricity and heat demand. Winter, Autumn and Spring, and Summer patterns are originated from the literatures (The Society of Heating 2015; Engineering Promotion Association, Underground Development Research Center 2017; Hashigaki 2010; Agency for Natural Resources and Energy 2011; Kiyota et al. 2002; Watanabe et al. 2010; Takashima et al. 2010) and corrected to the Rokkasho Village's pattern with climate data, facilities' floor space data, and electricity and fuel bills. The sums of electricity and heat demand of the months are equal to the values in electricity and fuel bill. The transitional seasons' patterns between Winter, Autumn & Spring, and Summer are mean values of two patterns.

43.4.2 Step 2. Fuel Cell and Hydrogen Demand

Considering electricity demand of public facilities and houses, the fuel cells to be installed is selected from currently available products. As a result, one 100kWe size PEM (Proton Exchange Membrane) fuel cell is installed to each public facility and one 0.7kWe size PEM fuel cell is installed to each house.

Output of FCs are determined based on electricity demands of facilities, the FC electricity output in every hour is maximum output that does not excess the electricity demand of the facility. The heat output and hydrogen consumption are subordinately calculated from the electricity output. The yearly total of hydrogen demand in 0.7 kW fuel cells is 2,659,366 Nm^3 and that of 100 kW fuel cells is 2,374,100 Nm^3.

43.4.3 Step 3. Power Generation Pattern

Photovoltaics and wind power locate in Rokkasho Village are utilized for power source of hydrogen in this study. Specific power generation patterns of renewables are normally unavailable. So here, the authors suppose the power generation patterns from public data. Solar radiation intensity and wind speed data are got from NEDO METPV-11 database (NEDO 2019). The capacity of PV panels and wind turbines are the sum of existing power stations in 2016 (Agency for Natural Resources and Energy 2019).

The output of PV power generation *PVout* in every hour t is calculated from formula (43.1):

$$PVout_t = Cappv \times \frac{Rad_t}{Radmax} \tag{43.1}$$

In formula (43.1), *Cappv* means capacity of PV panels, Rad_t is Solar radiation intensity in hour t and *Radmax* is maximum solar radiation intensity in the year.

In order to assume power generation from wind power, the capacity, power generation curves of turbines, and wind speed pattern at the turbine nacelle height are required. The authors set the turbine unit capacity as 3 MW and the power generation curves of the turbine from a literature (Wenning and Kissock 2009). The sum of existing turbines is rounded up to an integral number of 3 MW turbines, which is the total capacity of the wind power station. The height of turbine nacelle is assumed as 80 m from the sea level uniformly. The wind speed on the ground at hour t $WS_{ground,t}$ from the NEDO database is converted by formula (43.2) to that at 80 m high. The power multiplier p is 0.38, which is Rokkasho Village's data from a literature (Yokohama and Kodama 2013). $WS_{h,t}$ means the wind speed at the height h and hour t, *ground* means the ground altitude from sea level.

$$WS_{h,t} = WS_{ground,t} \times \left(\frac{h}{ground}\right)^p \tag{43.2}$$

Table 43.2 The outline of renewable energy

	PV	Wind	Synthetic
Capacity (kW)	168,000	147,000	315,000
Max output (kWh/h)	168,000	147,000	313,400
Median of output (kWh/h)	1067	27,979	40,000
Capacity factor	15%	28%	21%

As a result, Table 43.2 shows the outline of renewable power generation.

43.4.4 Step 4. Hydrogen Production Pattern

In step 4 and 5, hydrogen production pattern and hydrogen storage capacity are assumed in trial and error manner.

In this study, as Fig. 43.1, upper and lower thresholds are set on the synthetic power generation pattern of PV and WP. Here, threshold is indicated by the percentage to maximum output of renewable energy. The gap between the two thresholds is rounded up the digit of 10 kW to the capacity of electrolyzer, and the pattern between the thresholds is potential electricity input pattern to electrolyzer. Hydrogen production pattern is determined by the capacity and efficiency of electrolyzer, potential electricity input pattern, and capacity of hydrogen storage. In this study, the energy efficiency of electrolysis is assumed as 4.5 kWh/Nm^3-H_2. And electrolyzer consumes 0.02t water to generate 1 Nm^3 hydrogen.

The authors set four cases for this study as Table 43.3. Case A utilizes stable part of the power generation pattern. The lower threshold is 0%. Case B collects variable part of the power generation pattern. The upper threshold is 100%. In case C and D, the median of power generation pattern is the lower threshold. In case D, when needed, the thresholds are lowered to increase hydrogen production volume.

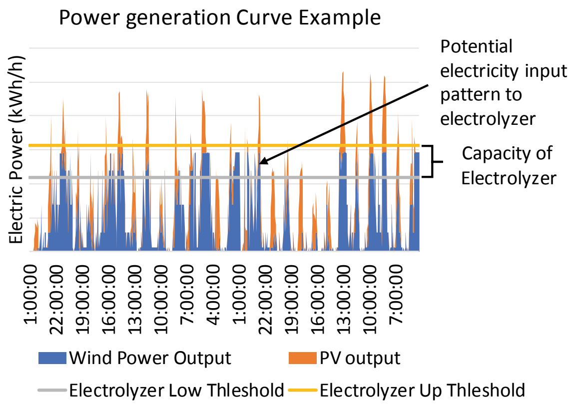


Fig. 43.1 Example of power generation curve

Table 43.3 The outline of study cases

Case	Threshold
A	"Stable" Lower threshold is 0%
B	"Variable" Upper threshold is 100%
C	"Median" Lower threshold is nearly median
D	"Median + threshold shift" Lower threshold is nearly median and including lowering the thresholds when needed

43.4.5 Step 5. Capacity of Hydrogen Storage

In this study, pressurized hydrogen tank is used for storing hydrogen and using pipeline to distribute hydrogen. The hydrogen output from the electrolyzer are stored directly in the tank. In order to minimize the total length of the pipeline, the tank is located around the houses and public facilities. Following the high-pressure gas safety law of Japan, maximum pressure of the tank is set as 1MPaG. 5–95% of the tank capacity is utilized.

43.4.6 Step 6. Unit Cost of Hydrogen

In order to calculate unit cost of hydrogen, the authors used Levelized Cost of Hydrogen method (see Formula (43.3)). The value of parameters to calculate the cost is shown in Table 43.4, which includes cost down of facilities in 2030. Renewable electricity cost is different among cases. Stable electricity is assumed expensive and variable electricity is assumed cheap. In this study, taxes and profits of hydrogen supplier are not counted.

$$\mathrm{LCOH} = \sum_{n} \frac{\sum_t \left\{ \left(I_{n,t} + M_{n,t} \right) (1+r)^{-t} \right\}}{\sum_t \left\{ E_t (1+r)^{-t} \right\}} \tag{43.3}$$

The list of the valuables are as follows:

- $I_{n,t}$: CAPEX of facility (process) n in period t.
- $M_{n,t}$: OPEX of facility (process) n in period t.
- E_t: Hydrogen production in period t.
- r: Discount rates.
- t: time period (1 year unit).

Table 43.4 Parameters t o calculate cost

Item	Value	Source
Unit cost of electrolyzer	50,000 JPY/kW	Council and on Renewable Energy (2017)
Unit cost of hydrogen tank	4,200 JPY/Nm^3	Chubu Gas Corp (2005)
Operating period	15 years	
Discount rate	3%	
Maintenance cost rate	5%/year (to facility cost)	
Cost of electricity	10.0 JPY/kWh (Case A) 2.5 JPY/kWh (Case B) 5.0 JPY/kWh (Case C, D)	
Cost of water	45 JPY/t	Aomori Prefecture (2016)
Pipeline cost	300,000,000 JPY (total 3.0 km length)	

43.4.7 Step 7. Economic Feasibility

Hydrogen generates 2.94 kWh/Nm^3 (Lower Heating Value basis) of energy when combined with oxygen. We can utilize part of it as electricity and heat as hot water. In this study, equivalent value of hydrogen to grid electricity and fuel oil is the boundary of economic feasibility. For example, as shown in Table 43.5, 1 Nm^3 of hydrogen is equivalent to 1.44 kWh of grid electricity and 1.35 kWh of heat from fuel oil, which is used in 0.7 kW fuel cell. When grid electricity is 10 JPY/kWh and heat from fuel oil is 3 JPY/kWh, hydrogen used in 0.7 kW fuel cell has equivalent value of $10*1.44 + 3*1.35 = 18.45$ JPY/Nm^3.

The grid electricity and fuel oil prices in this study are shown in Table 43.6. The cost in 2016 is got from a website (Tohoku Electric Power Co and Inc. 2019), the average of real electricity bills of public facilities, and statistics (Agency of Natural

Table 43.5 Spec of fuel cell and value of hydrogen

	0.7 kW fuel cell	100 kW fuel cell
Efficiency (electricity)	49%	50%
Efficiency (heat)	46%	46%
Electricity equivalence of hydrogen (kWh/Nm^3)	1.44	1.47
Heat equivalence of hydrogen (kWh/Nm^3)	1.35	1.35

Table 43.6 Grid electricity and fuel oil

	Grid electricity (houses)	Grid electricity (business)	Fuel Oil
Price in 2016	26.0 JPY/kWh	22.3 JPY/kWh	78.4 JPY/L
Price in 2030	48.4 JPY/kWh	41.5 JPY/kWh	145.8 JPY/L
LHV	–	–	36.7 MJ/L
CO_2 intensity	0.523 kg-CO_2/kWh		2.49 kg-CO_2/L

Resources and Energy 2019). In 2030, electricity and fuel oil price are assumed 1.86 times higher than 2016, which is based on crude oil price assumption in "450 Scenario" in World Energy Outlook 2016 (IEA publications 2016).

43.4.8 Step 8. CO_2 Emission Reduction

In this study, hydrogen consumption volume is the same among the four cases. CO_2 reduction effect is calculated as replacement of grid electricity and fuel oil consumption with hydrogen. CO_2 intensity of grid electricity and fuel oil (Ministry of Environment 2019) is shown in Table 43.6 and that of hydrogen is 0. Formula (43.4) gives the CO_2 emission reduction CO_2red from electricity and heat.

$$CO_2red = EqH_2 \times C_{H2} \times CO_2int \tag{43.4}$$

Here, EqH_2 means electricity/heat equivalence of hydrogen, C_{H2} means hydrogen consumption, and CO_2int means CO_2 intensity of grid electricity/fuel oil.

43.5 Result of Case Study

43.5.1 Size of the System

Table 43.7 shows the capacity of electrolyzer and hydrogen tank of the cases. The capacity of electrolyzer differs from 3.8 to 188.1 MW. The capacity of hydrogen tank differs from 25,000 to 150,000 Nm^3. As Case A, when uses stable part of renewable energy, small electrolyzer and hydrogen tank is enough for meeting the hydrogen demand. The capacity factor of electrolyzer is high. In contrast, case B tells that when only "excess" electricity is used for hydrogen production, the required size of electrolyzer become huge and capacity factor of it becomes to only 1%. The intermediate case such as case C and D is reasonable choices for PtoG system operation.

Table 43.7 The capacities of the cases

	Case A	Case B	Case C	Case D
Thresholds	0–1.2%	40–100%	12.8–16.0%	12.8–15.5%, 12.0–14.7%
Capacity of electrolyzer (MW)	3.8	188.1	10.1	8.5
Capacity of hydrogen tank (Nm^3)	25,000	150,000	40,000	40,000
Capacity factor of electrolyzer	65%	1%	25%	31%

43.5.2 Economic Feasibility

Figure 43.2 indicates the economic feasibility. The four stacked bars indicate the hydrogen cost in the cases and the four horizontal lines indicates the boundary of feasibility, the equivalent value of hydrogen to grid electricity and fuel oil used in 0.7 kW and 100 kW fuel cells in the year 2016 and 2030. The hydrogen cost differs from 48.0 to 301.8 JPY/Nm^3. Case A, C, and D is feasible in 2030. In 2016, the cost of Case D is lower than equivalent value in 0.7 kW fuel cell, the others are higher than the boundary. Case B is not feasible in 2030.

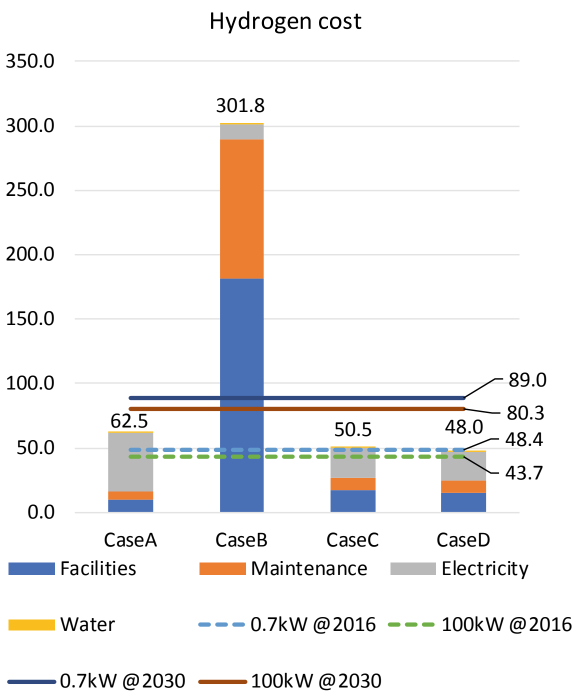


Fig. 43.2 Economic feasibility

Compared to the current hydrogen cost level, case A, C, and D are cheaper than the hydrogen retail price, 100 JPY/Nm^3 for fuel cell vehicle. Depending on the additional transport and compression cost, hydrogen in case A, C, and D can be domestic transport fuel. Compared to the Japanese national target, hydrogen costs in this study is higher than the 2030s imported hydrogen cost target, 30 JPY/Nm^3. However, this target does not include domestic distribution cost.

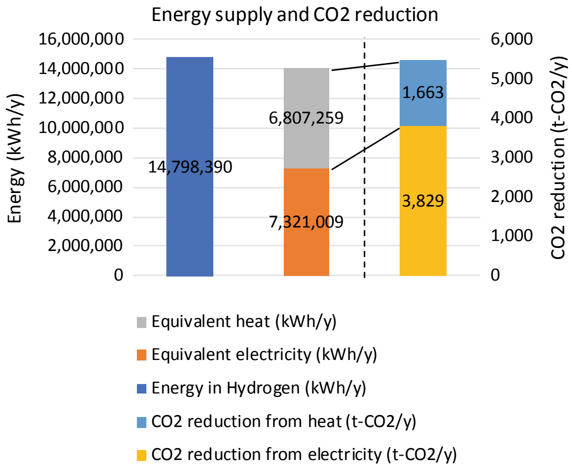
43.5.3 CO_2 Emission Reduction

In this system, 5,033,466 Nm3 of hydrogen is consumed every year. This amount of hydrogen replaces 7,321,009 kWh of grid electricity and 6,807,259 kWh of heat, which is equivalent to 667,742 L of fuel oil.

As a result, CO_2 emission reduction effect of this PtoG concept in Rokkasho Village is 5,492 t-CO_2/y. 3,829 t-CO_2/y is from electricity and 1,663 t-CO_2/y from fuel oil.

As Fig. 43.3 shows, the amount of equivalent electricity and heat is nearly equal but the CO_2 emission reduction of electricity is more than twice larger than that of heat. This result indicates that in order to reduce CO_2 from residential and public sector of Rokkasho Village, CHP is effective. However, this result depends on the CO_2 intensity of grid electricity.

Fig. 43.3 Energy supply and CO_2 reduction



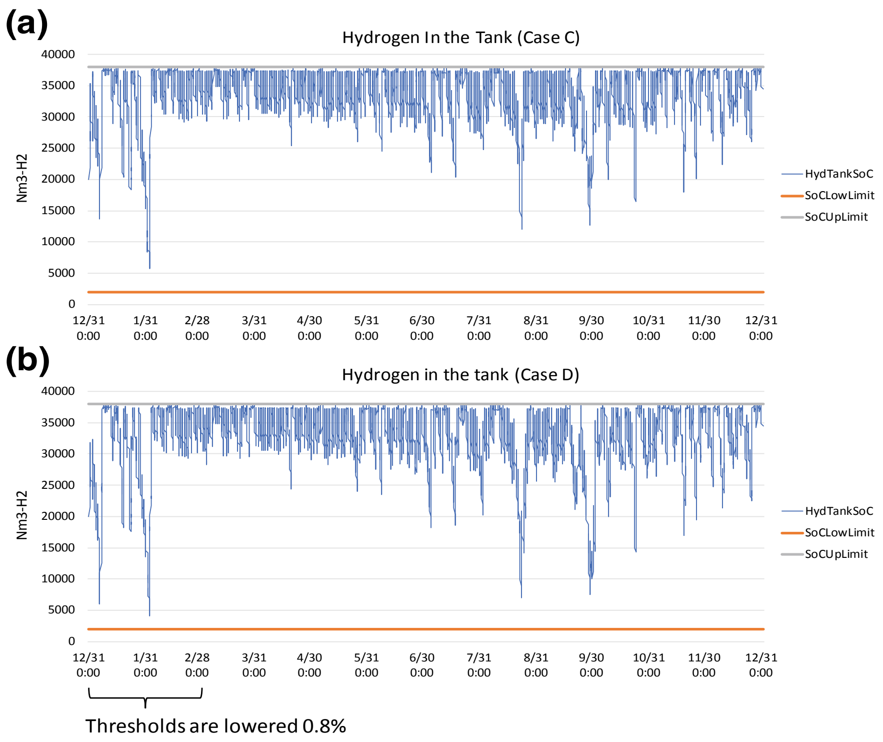


Fig. 43.4 Energy balance in case C and D

43.5.4 Effect of Threshold Shift

Figure 43.4 gives the effect of threshold shift of electricity input to the electrolyzer. As Fig. 43.4 shows, there are several short periods when hydrogen level in the tank is low. It is because of shortage of renewable energy supply. In case D, as (b) in Fig. 43.4, when thresholds are lowered 0.8% in January and February, 15% reduced capacity of electrolyzer is enough for balancing the hydrogen supply and demand (see Table 43.7). This effect is reflected to hydrogen production cost difference in 2.5 JPY/Nm^3. This tells that the control of electrolyzer can contribute to reduce the hydrogen cost.

43.5.5 Possibility of Further Application

Figure 43.5 shows the yearly total of hydrogen production potential and actual production. In each case, there is gap between the potential and the actual production. This gap comes from the time lag of hydrogen production and consumption,

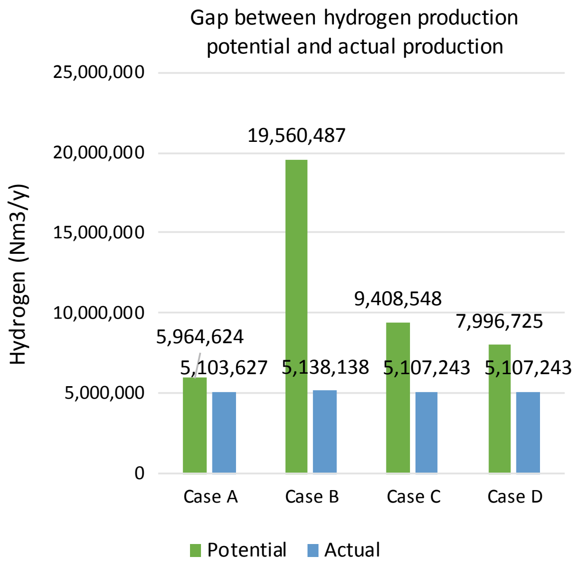


Fig. 43.5 Gap between hydrogen production potential and actual production

and the capacity of hydrogen tanks. This gap is, for example, can be utilized in fuel cell electric buses and vehicles to reduce CO_2 reduction in transportation. This idea is effective for Rokkasho Village, which depends on car transport like other many rural areas in Japan.

43.6 Discussion

Comparing to other existing Power to Gas demonstration sites in Japan Ohhira (2019), the proposed concept is unique in building a new hydrogen pipeline network in residential areas. This is intended to replace the fossil fuel and labor-intensive existing infrastructure, which is well-seen in Japan, with a low carbon and automatic one.

In order to realize such a Power to Gas system, both policy support and technological advancement are required. For example, reasonable safety guidelines for hydrogen pipelines in residential area and inexpensive materials, design, and construction method following the guideline are needed. For reducing footprint of facilities, high-pressure and high capacity electrolyzer is important. The overall system reliability must be improved to apply the system to communities including medical facilities.

For the economic feasibility of the system, both advancement and cost reduction of facilities and electricity cost reduction are required. The latter depends on policy and rule making of "excess" electricity market.

43.7 Summary

This study proposes a Japanese Power to Gas Concept and assumed feasibility of that. The proposed concept is economically feasible under the specific situation. The points of feasibility study are as follows:

1. Hydrogen from only "excess" electricity is too expensive even in the future, the energy cost become higher than the present.
2. Intelligent control of electrolyzer will contribute to lowering the cost of hydrogen.
3. Hydrogen combined heat and power reduces more CO_2 than just supplying heat from hydrogen, but it depends on CO_2 intensity of grid electricity.

Future analysis includes more sophisticated and realistic simulation of Power to Gas system, such as using real electricity and heat demand pattern, analysis under variable electricity price, and analyzing the effect of battery buffer for electrolyzer.

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Correction to: EcoDesign and Sustainability II

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In the original version of the book, the following belated corrections have been incorporated:

In chapter "Embedding a Sustainability Focus in Packaging Development Processes", the author group was incorrect. The author group "Kenichiro Chinen, Hideki Endo, Mitsutaka Matsumoto, and Yongliang Stanley Han" has been changed to "Bjorn de Koeijer, Iris Borgman, Jörg Henseler, Roland ten Klooster, and Jos de Lange" in the Frontmatter, Backmatter and in the Chapter.

In chapter "Consumer's Perception of Plastics in Everyday Products in Relation to Their Personality", the author group was incorrect. The author group "Kenichiro Chinen, Hideki Endo, Mitsutaka Matsumoto, and Yongliang Stanley Han" has been changed to "Lore Veelaert, Els Du Bois, Laure Herweyers, and Ingrid Moons" in the Frontmatter, Backmatter and in the Chapter.

This has been corrected in the updated version.

The updated version of these chapters can be found at
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