Allen H. Hu · Mitsutaka Matsumoto
Tsai Chi Kuo · Shana Smith *Editors*

Technologies and Eco-innovation towards Sustainability II

Eco Design Assessment and Management

Springer

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Part I

Social Aspects in Eco-Design and Sustainable Consumption

Chapter 1
Perspectives of Knowledge Translation Within Sustainable Product Development

Harald E. Otto

1.1 Introduction

The knowledge production and advanced technology of modern science and engineering have provided a means not only of better understanding and predicting our physical world but also of rapidly exploiting, influencing, and partly controlling it in order to achieve a safer, more comfortable, and more pleasant life. A closer look at the current formation of knowledge-producing environments in both academia and industry, which partially characterize the present position within the evolution of science and engineering, reveals that among several newly emerging paradigms, four seem to have acquired a dominant role, namely, knowledge economy, sustainable development, science and engineering for the postmodern age, and reverse knowledge transfer and innovation. Here, improvements and advances in awareness and comprehension of not only the nature but also the relations between fields of knowledge are necessary. That also applies to novel and innovative ways to more effectively integrate both knowledge and expert views from various disciplines and fields of expertise. Considering sustainable development, possibly more relevant yet, though, is developing better and more efficient approaches for an understanding on how knowledge and expertise that are stemming from academic research and industrial practice can be translated and employed for policy-making and problem-solving within postmodern society. Nowadays, many research-related projects and programs of most disciplines within postmodern engineering science are more and more coming under critical observation and inquiry in regard to their goal settings and results. Apparently, this increased scrutiny is mostly aimed at determining and making transparent, whether dominant elements of those results in the form of knowledge and artifacts do actually benefit society, while also adhering to the principles of sustainable development and

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(engineering) science. Those circumstances, in turn, force today's research projects and programs to build multidisciplinary alliances of a transformative nature consisting not only of scientists and engineers but also practitioners and policy-makers. Those lately allied actors and stakeholders are now expected to positively influence the problem definition process and subsequent actions leading to approach selection, solution generation, and translation of the solution into practice, in a way that is consistent with goals and principles as outlined above.

Unfortunately, prevailing trends and current tendencies are telling otherwise. Difficulties and problems of what is in the literature termed the *know-do gap*, i.e., what we know and what is actually being done, are not only due to ignorance at individual and organizational levels and prevailing outdated legacy systems in developed countries but also due to the complexity of the systems, processes, and technologies involved in today's problems and their possible solutions and, of course, the knowledge related to these. Therefore, gaps and flaws in the knowledge flow and understanding within policy-making processes are unavoidable. Under these current difficult conditions, knowledge translation as a central paradigm in the wider context of translational and implementation science is now widely regarded as a means for solving many issues of the know-do gap. Knowledge translation is also considered being capable of supporting policy-making by transforming its processes as to attain a more meaningful and satisfactory level.

However, despite the potential of knowledge translation for supporting efforts aimed at reducing the know-do gap, prevailing issues in current practice, such as a lack of know-how in employing systematic methods and knowledge-based frameworks and tools, impede most of the anticipated and awaited progress in this direction. Selected aspects pertaining to these issues are discussed in this chapter as follows: First, important types of knowledge are identified, and their modes of creation are discussed and related to invention and innovation. Next, methods and frameworks aimed at bridging knowledge creation and its outcome with actual implementation and use in practice are presented and analyzed. This creates the base for a critical view on individual aspects of knowledge translation relating to knowledge flows and innovation pathways. Also included are issues of reverse knowledge flows and the balancing of learning with unlearning during translational and adoption processes, as these are becoming increasingly relevant for new modes of knowledge creation and reverse innovation.

1.2 Knowledge, Innovation, and Mode of Creation

1.2.1 Types of Knowledge and Their Creation

In general, the concept of data refers to any existing form of information or knowledge, which is coded or made explicit in a way that qualifies for processing. Within a given context, data becomes information as a result of interpretation. Knowledge, in turn, can be obtained through the use of considerable experience related to domain subject information. Knowledge, in general, is comprised of structured information that is organized and thus not always easy to codify. Even today, despite astonishing advances in information and communication technology (ICT), much knowledge still remains tacit due to its complexity and its manner of organization related to its embodiment, which is not yet fully understood. In engineering science, domain knowledge, in particular, is usually more specific than in other areas of science, as it relates to particular applications. Transfer of this kind of knowledge to different situational contexts cannot be achieved automatically. Engineering knowledge, sometimes referred to as *technological knowledge* in the literature, represents a collection of various types of knowledge, containing sorts of knowledge that do not exist in other scientific disciplines (see also [1, 2]). For instance, technical knowledge and skills related to how an artifact or process needs to be operated and how they work and behave are such examples. Those technical skills and knowledge are referred to as *know-how* in the literature (for early original work, see [3]). Here, it must be pointed out that this kind of knowledge is inculcated, because usually one is able to complement and refine as well as hone partial know-how and remedy misunderstandings, hence, representing a typical exercise in developing expertise and competence. In a more general sense, know-how is always embodied in individual persons or in organizations, signifying the level of practical attainment and expertise.

Knowledge also comprises norms, that is, knowledge about the nature and properties of functional aspects regarding an artifact or a process in the technical context and knowledge about social norms and cultural values in the socio-cultural context. All forms of normative knowledge that are related to propositions, which, for example, are dealing with effectiveness and efficiency, are not able to handle assertions of truths and therefore usually cannot be found in other scientific disciplines. However, knowledge that is represented in a graphical and visual manner in the form of drawings and diagrams constitutes an almost quintessential segment of technological knowledge. In the literature this particular type of knowledge is sometimes also referred to as *visual knowledge* (cf. discussions in [4]). All forms of declarative and procedural knowledge made explicit through formal or informal notations, including all types of numerical data and formulae, comprise an essential part of knowledge that exists in all academic disciplines covering not only engineering and sciences but also the humanities and economics. In the literature this type of knowledge is also referred to as *propositional knowledge* or *knowing-that*. This represents a type of codifiable knowledge that is usually encountered in a disembodied form. It needs to be made explicit here that the nature of this kind of knowledge is of a sort of being imported, because one knows that or not. This stands somewhat in contrast to know-how, within which particular subjects of knowledge and skills evolve in various developmental stages. Although having outlined and summarized some of the most characteristic features of scientific, technological, and engineering knowledge, the discussions above have neither elaborated on nor given any specific details on its contents, as this would avowedly exceed the scope of this brief introduction. Nevertheless, for obtaining a deeper and more detailed overview and a better understanding on this issue, it is recommended to study the taxonomies, expository viewpoints and discussions, and further readings presented in [5, 6].

The rapid ascent of advanced knowledge economies has reshaped both the economic dynamics and values and the inherent features and characteristics of society. As recent developments show, knowledge has become the dominant resource in regard to not only business models but also products and services. As a consequence, innovation and, closely related to it, processes of knowledge creation, transfer, and exchange have gained a rapidly growing interest in different circles ranging from research administrators and economists to decision-makers and policy-makers. The traditional approach of creating knowledge within an autonomous academic setting based on the Kantian belief in disciplinarity and the Humboldtian approach of linking education and research, where scientific research is driven by curiosity and dispassionate inquiry, represents a closed epistemological circle, neglecting the need for solutions of real-world problems and the translation of newly created scientific knowledge to society at large. This kind of traditional knowledge creation, in the postmodern era termed *Mode 1* knowledge creation, is now challenged by interdisciplinary and transdisciplinary research approaches referred to as *Mode 2* knowledge creation, which are aimed at addressing shortcomings of traditional academic research (cf. [7–10]). It is considered that Mode 1 knowledge creation fails to meet present-day challenges, partly due to excessive specialization and lack of societal relevance and accountability. Within this new shift in knowledge generation, which is increasingly intertwined among academia, government, and industry [11], the outcome is assumed from the beginning to be part of the context of application, and thus, in theory, it requires far less translation, or none at all, of its results in order to be applied. However, this new mode of knowledge creation supporting systematic research collaboration, while also providing a relevant and cost-effective input for innovation, obviously becomes increasingly subject to policy issues and national research priorities, thus diminishing the pursuit of knowledge as a public good.

1.2.2 Invention and Innovation

In general, an invention is a novel device, method, or process, which often extends the boundaries of human knowledge and capability. Invention is also considered an exploratory and creative process, sometimes with an uncertain or unknown outcome, which often involves combining various concepts and elements from different fields and disciplines. As an invention may serve various purposes, it does not necessarily create positive value and further progress in a given area of development. Related to invention is innovation, which is often simply described as a novel idea, tool, or method, which is possibly seen as the employment and utilization of improved and more effective, as well as more efficient, solutions introduced into markets, governments, and society. In the literature, innovation is often revealed and expressed through engineering processes and viewed as both a process and an outcome (see also [12, 13]). Two main dimensions associated with innovation are as follows: first, the grade and extent of novelty, that is, if an innovation is novel to the organization and to the industry where it was developed and adopted or novel to the world, and second, the class of innovation, that is, if it is a product system innovation linked to goods and services or a process innovation. In particular within the context of organizations, innovation can be related to transformations that improve the efficiency and the productivity, thus also enhancing the competitiveness. Moreover, late research in this direction underlines the important role of organizational culture and its complementary capacity for enabling organizations to render activities linked to innovation into improvements of tangible performance [14].

Within the context discussed in this chapter, the conceptualization of innovation differs from that in traditional innovation literature, which defines innovation on the base of an outcome that is knowledge-based as described in [15]. Within such an approach, innovation as an artifact is assumed to contain the knowledge that is required for both the understanding of how it has been created and the ability to create it again. Therefore, innovation as an outcome is defined by knowledge, which was produced during the innovation process. This knowledge, in turn, provides impetus that permits the process to be not only interpreted and comprehended but also replicated. As innovation is determined as a knowledge-creating process with a particular outcome, namely, the knowledge that was created, this newly created outcome needs to have certain properties, as not all newly created knowledge represents an innovation. These characteristics defining the knowledge that is considered as the innovation-defining outcome are as follows: first, having duplicability; second, being new in the context to which it is introduced; and third, having a demonstrated usefulness. More details on and a thorough discussion of these three defining characteristics are given in [15].

1.3 Processes Putting Knowledge into Action

1.3.1 Knowledge Translation and Transfer

Work and research on methods and frameworks aimed at closing the gaps between academic knowledge creation and the actual use of its outcomes in practice, in other words knowing how to put knowledge into action, is identified in the literature with many terms. As already pointed out and suitably formulated in ([16], p. 211), this “translational research means different things to different people, but it seems important to almost everyone.” It comes as no surprise, then, that more than 90 terms have been identified through literature analysis (cf. [17]), indicating a certain preference of terms related to geographic location as follows. For example, according to findings referenced in [17], the terms implementation science and research utilization are commonly used in continental Europe and the United Kingdom, while in Canada there is a noticeable preference for knowledge translation and exchange. In the United States, mostly the terms knowledge dissemination and diffusion, research use, and knowledge transfer and uptake are used. Despite the considerable variety in definitions given and terms used, the common core of understanding is a need to move beyond the basic dissemination of scientific and academic knowledge, usually pursued within academic presentations and publications at conferences and in journals, to ensure a more timely and valued use of knowledge in administration, informed decision-making, policy-making, and practice and services within society. Another point worth mentioning here is that knowledge translation should not be confused with related activities such as technology transfer and commercialization of scientific and academic knowledge or educational interventions (see also discussions in [18, 19]).

Current efforts in knowledge translation are guided by key questions such as what knowledge should be transferred to whom by which actors and means, and with what effect this knowledge should be transferred (cf. [19, 20]). Models promoting the application of translational research and supporting the process of knowledge translation, such as the knowledge-to-action framework already adopted by CIH-Research in Canada, (see [17, 21]), provide stimulating examples of outcomes contributing to the science and practice of knowledge translation. In this context, the concern and activity are not novel, but as an academic endeavor becoming more widely recognized and established, this represents a relatively new field.

1.3.2 Knowledge Brokering and Interaction

Another variety of activities aiming to link the creation of scientific evidence and academic knowledge to the potential application and actual use of such knowledge in non-academic contexts and practice is referred to as *knowledge brokering* (cf. [22–24]). One of the main roles of knowledge brokering is seen in the facilitation of interaction within access to and transformation of scientific expertise to enhance industrial processes, public services, and regulatory processes by connecting academic research and its outcome with decision-making and policy-making. Here knowledge brokering specifically aims to address barriers related to the limited capacity at the user end to access and to properly assess scientific and academic knowledge in regard to quality and relevance for a given application context. Although knowledge brokering is presently experiencing a considerable boom in various public and service sectors, it has, in fact, been operating in the private sector for many years (cf. [23, 25]).

Within knowledge brokering the human component is seen as the most central and important element, as knowledge brokers work as much as possible at the interpersonal level and in collaboration with researchers, scientists, and key stakeholders, in order to facilitate the transfer and exchange of knowledge in a given context. Knowledge brokering is widely assumed to be an act of linking people to people, or linking people to information, in order to share learning, or to better understand others' goals or professional cultures, to influence others' work, and to forge new partnerships [26]. Here, to remain effective, knowledge brokers are required to invest in regular personal interaction, mutual learning, and collaborative agenda setting, if long-term mutually beneficial partnerships are to materialize, wherein newly created scientific knowledge, being identified as adequate and valuable for an application domain, can be transferred and made useful within a meaningful time scale. In practice, knowledge brokering is becoming more systematic and being more widely recognized in academic circles, thus contributing to a better understanding of its role. However, theoretical insight and empirical evidence concerning the potential and effectiveness of knowledge brokering are still limited (see also discussions in [24, 27]).

1.4 Innovation Pathways and Organized Knowledge Flows

1.4.1 Outline

Knowledge translation has many dimensions, being related in varying degrees to aspects of problem identification, knowledge creation, transfer and exchange, and thus to the flow of knowledge and the pathway of innovation. Determination of problem identification and research targets for innovation and knowledge creation in general are not value-free, as their nature depends considerably on who identifies and selects them in the first place. This situation was generally, and still remains for some particular non-technology-related disciplines, less critical in the case of Mode 1 knowledge creation within academic research. However, it is quite pronounced in the case of Mode 2 knowledge creation and reverse innovation.

In the following subsections, aspects of learning, unlearning, and knowledge organization and representation are discussed in relation to knowledge translation. Such knowledge is not limited to Mode 1 and Mode 2 but also includes innovation, in particular reverse innovation, as a knowledge-based outcome.

1.4.2 Learning, Unlearning, and Innovation Adoption

Within the context of innovation in sustainable product development, in many instances, the direction and priority of problems seem to be defined without any awareness of solutions already in place and in contexts and geographical locations different from those in the global North. The knowledge as well as the scientific evidence may indicate the possible potential of improvement along alternative directions, which thus remain either overlooked or ignored. This situation is also evident in current efforts to harness reverse innovation as a means to support the creation of new approaches and solutions. Here elements of genuine learning and understanding offer examples of shortcomings which are still widely prevalent. There is a tendency to focus mostly on economic and technical issues to translate solutions developed and successfully applied in developing countries into interventions and subsequently solutions for problems in developed countries. For example, frameworks and models for reverse innovation, as proposed in [28], approach the first step of the reverse innovation pathway by identifying successful innovations in developing countries that have the potential to address an unmet need in a developed country. However, they remain ignorant of solutions that indeed could remedy problems in the global North, because their value has not been recognized as their location and point of impact were previously not thought worthy of any major effort. If their true value were recognized, they would be given a higher priority on the decision-makers' agenda.

International partnership and exchange programs, and collaboration programs between developing countries and developed countries, increasingly feature a joint agenda with emphasis on mutual accountability and bi-directional learning. There is a need for genuine learning and understanding of agents from the global North by their counterparts from the global South. The barrier here is more of a socio-cultural nature and of latent attitudes, manifested at both the organizational level and the individual level. This represents a situation that reflects on the history of knowledge and technological development and the global flow of innovation. Until very recently, this unambiguously indicated who the holder of expertise and know-how was and what the correct and efficient way of doing things ought to be. In order to benefit from the opportunities within those programs, genuine learning from and understanding of unexpected sources need to be fostered, while at the same time, a change in long-standing attitudes related to who should learn from whom needs to be addressed by considering a reform of the self-interest motive and institutional learning related to those programs (cf. discussions in [29–32]). To overcome some of these barriers and proactively take steps toward benefiting from the potential that reverse innovation provides for learning and capacity building, innovations successful in supporting sustainable development occurring in developing countries must be recognized and translated into the context of developed countries. Efforts such as the competition-based reverse innovation challenges reported in [33] are recent examples providing promising results.

Another important element in the context discussed, besides learning, is unlearning [34, 35]. As learning is used to move toward something, usually a specific goal, by acquisition of knowledge and information, its counterpart, namely, reverse learning in the form of unlearning, is used to move away from something, in other words, to let go of what has been learned and acquired. As already pointed out in [36–39], the processes of unlearning are vital for any organization not only to successfully engage in innovation and knowledge creation but also to support and benefit from reverse knowledge transfer. Within knowledge transfer and translation, the type and degree of unlearning required depend obviously on the type of knowledge, the application context, and the domain (developed/developing country) the knowledge was developed in and is being transferred and translated to. Most work and frameworks on knowledge translation focus on Mode 1 and Mode 2 knowledge, though with the increasing interest in reverse knowledge transfer within multinational corporations across national borders, and with reverse innovation increasingly gaining international attention (cf. [28, 33, 40, 41]), innovation as a knowledge-based outcome needs to be included as well. Especially within reverse innovation, unlearning, either at the individual level or at the organizational level, is a widely neglected element that needs to be balanced with learning to realize reverse innovation through reverse transfer of translated knowledge. This will create benefit in developed countries from successful solutions produced in developing countries. When we conceptualize innovation as a form of an outcome that is knowledge-based, adoption of an innovation is related to knowledge, which is required for the replication of this innovation within a particular context [15]. If that knowledge is entirely available and can be used, the innovation can be adopted. However, if this knowledge needs to be entirely created again, adoption turns into innovation. In the case of reverse innovation, this situation is determined to a large extent by the degree of adaptation a product requires and the change/reorganization required for its ecosystem (cf. [41, 42]). Here again, unlearning needs to be balanced with learning. For example, many efficient and sustainable solutions created in developing countries cannot be translated and implemented in developed countries due to legacy systems and related legacy mind-sets, particularly in the energy, transport, and health sectors. An example within the health context is the model of community health workers (CHW), which has already been successfully implemented and employed in several countries in Asia and Africa within emerging or developing economies, such as Thailand, Bangladesh, Tanzania, and Ethiopia. This demonstrates in actual practice a highly efficient and effective use of available human, organizational, and financial resources. This model represents one of the first examples of many promising applications of reverse innovation, which could be widely and systematically adopted and embraced by developed countries. However, legal and regulatory hurdles, such as standards of care, tort liability, licensure, reimbursement, and task shifting, along with legacy mind-sets in the professions involved, are serious inhibitors to the introduction and scalable adoption of the CHW model as a reverse innovation which undoubtedly has both the potential and the means to contribute to sustainable product development. Especially here, unlearning is a necessary precondition before any progress can be made. This must be achieved not as a cognitive exercise of individuals but as a co-created moving away from the current outdated status quo, at various individual and organizational levels, with a focus on emptying and creating an opening that in turn supports learning and creativity as outlined earlier. This is because non-technological-purpose systems, such as legal arrangements, in contrast to physical systems, do not tend to amortize but only increase in complexity and bureaucracy, thus creating an ever-increasing inefficient and complex overhead.

1.4.3 Knowledge Organization and Representation

The process of designing sustainable solutions for real-world problems, and thus generating knowledge, has changed substantially in science and engineering practice. Consequently, the scope, purpose, and nature of the result have changed significantly as well. However, what has not changed is how significant the documentation of process activities, resources, and results is, especially in respect to knowledge gained. In particular, within sustainability science and engineering, an unprecedented amount of knowledge is translated into and used for innovative processes, services, and technologies aimed at facilitating and supporting sustainable development. This knowledge is often highly structured and interrelated, reflecting the multidisciplinary, interdisciplinary, and transdisciplinary nature of the generation process. Within such a scenario, various questions arise concerning not only the goals and sustainability of the current knowledge production process itself but also the quality, structure, and documentation of its outcome and how it came about.

1.4.3.1 Documentation of Knowledge

How well a problem is defined and adequately represented is central to its solution. As work both theoretical and experimental suggests, an adequate problem representation can guide interpretations of information related to the problem and support the integration of domain knowledge with problem types (cf. [43, 44]). Employing knowledge mapping tools, which are based on semantic networks or concept maps, can support this task. In this way the logical structure of a problem can be made explicit and graphically represented on a common and shared base, which allows access and dynamic formation of such a digital document by domain experts with different expertise. It can also facilitate the detection of knowledge gaps and missing expertise, required to solve a problem. Here, knowledge mapping techniques and tools as discussed, for example, in [45, 46] would be appropriate. Another document that lists the components of a solution would also be helpful, much in the way its counterpart the bill of materials (BOM) is for physical artifacts. However, in the given context, since the result generated is abstract, something similar to what could be named a bill of concepts (BOC), containing a list of the concepts used in all documents, together with an annotated cross-reference, would be the appropriate choice.

Besides information and knowledge pertaining to the definition and solution of a problem, knowledge about the problem-solving process and its participants should be documented to further aid insight and understanding. This would be useful, for example, during case studies after the problem-solving process is finished and participants in design groups or research projects are being reassigned to work on a new task. For instance, the history and development of the skills and expertise of individuals, and thus aspects of the development and final state of individual and collective intelligence as related to a given knowledge generation context, can be captured by trees of knowledge, which also provide a means of documentation that supports analysis of knowledge and expertise allocation. Finally, knowledge encapsulated in proposed solutions that is considered essential and significant, not only in respect to the problem definition, needs to be made as explicit and transparent as possible in an appropriate documented form using any of the knowledge mapping and visualization techniques discussed below. Then it will be accessible by various valuable stakeholders who have not actually participated in the generation process.

1.4.3.2 Mapping of Knowledge Contents and Structures

Concept mapping is one of a group of techniques, which includes semantic mapping and network mapping, for representing knowledge contents and understanding. Concept mapping employs a particular graphical node-link representation known as a *concept map* to enable visualization and externalization. This type of cognitive map was developed by Joseph Novak (cf. [47, 48]) and is aimed at fostering meaningful learning based on the assimilation theory of learning psychology, to which the nature of its epistemological ideas is also related. More recently, concept mapping supported by computerized tools such as *Inspiration* and *CmapTools* has been used successfully for capturing, representing, and validating knowledge (cf. [45, 48, 49]).

Concept maps consist of nodes, representing individual concepts, and arcs, a kind of relationship line, which together form a network of propositions that, in turn, visually represent statements about objects or phenomena either being experienced by our human senses, i.e., naturally occurring in the physical world, or only theoretical. Both concept nodes and linking lines are furnished with labels, which clearly identify their meaning and relationships. The spatial layout of concept maps features a hierarchical structure with the more general concepts, and inclusive concepts, appearing above the others, though the actual spatial structure always depends on the context to which the mapping process is related. In practice, to keep concept maps transparent and manageable, hierarchies are limited to about eight levels. For the mapping of more complex knowledge structures, cross-links between concepts in different concept maps can be used to create map structures that are beyond a simple two-dimensional spatial layout.

1.4.3.3 Mapping of Knowledge Sources, Assets, and Skills

Knowledge source maps represent relationships between valuable knowledge and experts and their locations in respect to an organization or research project regarding a specific task or problem domain. Graphical representations are in most cases realized as two-dimensional diagrams or graphs that depict those relationships in an easy-to-recognize manner. Knowledge asset maps usually employ diagrams to document and visually present the locations of knowledge assets. Since they are also a means to index and classify, and thus help organize an overview of knowledge assets related to an organization or project, locating and accessing information and knowledge relevant for a task can be made systematic and efficient. More details and several examples can be found in [46, 50].

Another approach to mapping knowledge assets and skills in a group or team was developed by Michel Serres, Michel Authier, and Pierre Levy and is called *trees of knowledge* (see [51]). It is implemented as computerized tools known as *Gingo* and *See-K*. Central to this knowledge map is a colored tree-shaped chart subdivided into blocks, with each block representing a knowledge object or skill assumed to be the asset of one or several group members. Here, a set of knowledge objects deemed to be a necessary asset in respect to a specific skill is called a *coat of arms* (blazon). The spatial structure of this knowledge map graphically represents how knowledge and skill assets are distributed in a population relating to an organization or project. For example, people having assets represented in a branch might be considered a specialized community. For more details, examples, and additional references, see [52].

1.5 Conclusions

With the rise of knowledge societies in industrial nations, along with the rapid development of innovation capacity in developing countries, and the nature of some elements and processes in science and academic research seemingly becoming similar to their counterparts in applied and industrial engineering and vice versa, the chances of and potential for possible synergies between them have opened up recently. Along with this have come the development and advancement of theories, frameworks, and computer-based tools in fields as diverse as knowledge transfer and exchange, knowledge representation, and integrative and interdisciplinary and transdisciplinary studies. The discussion of selected aspects pertaining to issues of bringing newly created knowledge into society to support sustainable development, along with pointers given, hopefully may make communities and various circles in academia, industry, and government more aware of these opportunities. It may also contribute to furthering progress in awareness and recognition of the importance of employing the outcomes of research on frameworks and computer-based tools to organize, represent, and exchange knowledge and research into knowledge brokering and implementation/translational science. However, this needs to be within a wider horizon and context, additionally taking into account not only Mode 1 and Mode 2 knowledge generation, as is currently almost exclusively done, but also innovations as knowledge-based outcomes. The latter, in the case of reverse innovation, represent acknowledged and proven solutions in individual domains, but they are being developed and adopted both far away geographically from developed countries and also outside their legacy systems.

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Chapter 2
Rethinking Sustainability Assessment: Incorporating the Ethical Dimension into Decision-Making

Hui-Ting Tang

2.1 Introduction

As human development continues to degrade ecosystems on a global scale, it has become apparent that we should take prompt action to reverse the trend toward unsustainability. “There is a widely recognized need for individuals, organizations and societies to find models, metrics and tools for articulating the extent to which, and the ways in which, current activities are unsustainable” [1]. Such challenge calls for more informed decision-making in all fields of human activities so that each of our undertakings can be planned and designed for a more sustainable and equitable future.

Sustainability assessment (SA) is sometimes termed as sustainability appraisal or sustainability impact assessment. In its simplest form, it is a tool that bridges evidence and decision-making. It is a methodology “that can help decision-makers and policy-makers decide what actions they should take and should not take in an attempt to make society more sustainable” [2].

This study proposes to investigate the wholeness of SA from the perspective of behavioral decision-making theories, which can be classified into quantitative and qualitative approaches. It is for sure useful to identify and quantify concepts including risk, risk probability, risk magnitude, consequences, and impacts. Using quantitative methods such as multi-attribute utility theory or cost-effectiveness analyses to provide detailed assessment and predictions in quantitative terms can support and strengthen the decision made.

However, in a world of emerging technologies and changing paradigms, we can no longer rely purely on mathematical representations of the decision to be made. SA currently in place often fails to give fair consideration to qualitative factors of

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more inherent nature, namely, the ethical issues relevant for sustainability. Examples of these issues include intrinsic vs. instrumental value in nature, anthropocentrism vs. biocentrism, environmental justice, and so on and forth. Such issues pose great concern, and a truly complete SA should include careful deliberation on them. This study will elaborate the logics and the need of incorporating the ethical dimension into decision-making toward sustainability.

2.2 Current Status of Sustainability Assessment and Its Potential Flaws

SA can be regarded as a process that informs and directs decision-making toward sustainability. The decision-making referred to here comes in forms ranging from individual choices in daily life to actions or policies at broader scales. The latter is indeed nothing short of a familiar subject in the field of impact assessment.

SA derives its origin from environmental impact assessment (EIA) and strategic environmental assessment (SEA) [3]. While EIA is used as an aid to decision-making on both public and private plans and projects to identify and evaluate the consequences of one economic activity on the environment [4], SEA is used to take account of the likely effects on the wider environment when developing policies and long-term programs [5]. As for SA, it is best considered an umbrella term encompassing a very broad scope of impact assessment practice [6], designed to include social and economic aspects in addition to environmental concerns. Inspired by the Earth Summit of 1992 in Rio de Janeiro, many countries now have national sustainable development strategies in place, and that has given rise to the appearance and prominence of SA.

Yet, over the years, it has been pointed out that many SA examples are merely examples of integrated assessment that have been “extended to incorporate social and economic considerations as well as environmental ones, reflecting a triple bottom line approach to sustainability” [7]. Methodologies for SA can even be classified into two main types: monetary aggregation method and physical indicators. The former is primarily used by economists, whereas the latter is commonly used by scientists and researchers [8]. Both are quantitative, and each of the two has its own flaws.

For physical indicators, they simplify, quantify, analyze, and communicate the complex and complicated information [9]. It is admitted that “indicators and composite indicators are increasingly recognized as a useful tool for policy making and public communication in conveying information on countries’ performance in fields such as environment, economy, society, or technological development” [10]. However, indicator choices may not be automatically linked to improved sustainability outcomes [11] since “indicators arise from values (we measure what we care about), and they create values (we care about what we measure)” [12]. They are often subject to the viewpoint and needs of the assessor [13] or information availability.

For monetary aggregation method, its “quantitative factors give numerical basis for decision-making, namely reduces decisions merely to monetary value placed on different choices” [14]. Such method at once suggests that benefits of ecosystem services to human well-being are judged using monetary values and the costs are calculated as externalities and that the trade-offs of the environment for economic gains and social benefits are acceptable. There has been a general concern that it is the environment that typically gets traded off for socioeconomic benefit in these cases [15, 16].

2.3 Incorporating the Ethical Dimension

2.3.1 *Sustainability Assessment: Correlation Between Concept and Practice*

SA pursues the goal that “plans and activities make an optimal contribution to sustainable development” [17]. However, the concept of sustainability is complex and multifaceted. With all its uncertainties and risks, sustainability is difficult to be assessed and measured as doing so is like “measuring the immeasurable” [18].

SA in use now heavily relies on the triple bottom line approach. The phrase “triple bottom line” was first conceptualized in 1994, and it stipulated that companies should prepare three different bottom lines consisting of three Ps (profit, people, and planet) to measure the financial, social, and environmental performance of the corporation [19]. In the field of sustainability studies, the three pillars take on a new meaning to include the economy, society, and environment, the three sustainable development goals identified in the 2005 World Summit on Social Development [20].

In SA practice, different alternatives are compared on the basis of subjectively chosen indicators that correspond to the three pillars of sustainability. Current SA seldom dives deeper to examine the potential interconnectedness between the pillars, running the risk of biased decision-making. As humans and the environment interact in complex ways, it is worth investigating the interrelation between them to enable more comprehensive SA.

2.3.2 *Evolving Views on Human-Environment Relationship*

The purpose of SA is to “provide decision-makers with an evaluation of global to local integrated nature-society systems in short and long term perspectives in order to assist them to determine which actions should or should not be taken in an attempt to make society sustainable” [21]. To provide a holistic portrait of relationship between nature and society, that is, between the environment and humans, multiple perspectives, or views, will be discussed below.

"The concept of an ecosystem provides a valuable framework for analyzing and acting on the linkages between people and their environment" [22]. An ecosystem is "a community of animals and plants interacting with one another and with their physical environment" [23]. Yet, all too often, an ecosystem is viewed as a service provider, encouraging particular attention on the benefits of ecosystems to humans with regard to how the processes of nature deliver supplies and goods [24, 25]. Human-environment relationships are perceived and valued through ecosystem assessments that focus on an economic quantification of the costs and benefits of providing those ecosystem services and goods [26, 27].

The ecosystem services approach has become the dominant valuation tool applied for different purposes in various resource management contexts, including structuring strategic policy guidance and priority setting using multi-criteria assessments [28] and green accounting methods [29]. Conservation ecologists, biologists, and planners also use it to get their messages across to the public and implement environmental management strategies [30, 31]. However, such conceptual metaphor of economic production (i.e., ecosystems as providers of services and goods) has come under critiques. This metaphor emphasizes a consumption-oriented conceptualization of ecosystem. It represents too narrow a set of values and apparently denies the important role that humans play in maintaining and restoring the ecosystem capacity and functions [32, 33].

Since monetary considerations alone are not adequate to propel environmental management [34], it is gradually recognized that humans hold multiple values and views for nature. It has been pointed out that "the modern dogma is comfort at any cost" and that "we abuse land because we regard it as a commodity belonging to us. When we see land as a community to which we belong, we may begin to use it with love and respect" [35]. This echoes the web-of-life concept, which has a strong biological connotation. It indicates that a "web of complex relations" binds all living things because species are highly ecologically connected [36]. Humans, without exception, are one part of a wider ecological system. In short, all things in an ecosystem are interrelated and interdependent. This view is found not only in biology but also in many indigenous worldviews. For example, *hishuk' ish tsawalk* ("everything is one and all is interconnected") [37] is the view held by Nuu-chah-nulth First Nations at Tofino, Vancouver Island in Canada.

Though "all creatures, including humans, are interconnected in the web of life" [38], "humans have historically exploited plant and animal species in order to maximize short-term profit, at the expense of sustainability of the species or population" [39]. Fortunately, we have gradually come to recognize that we have overharvested and disrupted food webs. To compensate the misdeed, we have been trying to restore and enhance wildlife populations and food webs. Many ecosystem services researchers and conservation practitioners now hold the view that human-environment interaction includes "both beneficial and detrimental relationships and feedbacks" and that "humans have always had a close relationship with the natural environment. This relationship includes both supporting and degrading activities that lead respectively to benefits and costs to human well-being" [33].

2.3.3 Environmental Virtue Ethics

Since the human-environment relationship is intertwined and mutually reinforcing, humans, as part of a much broader ecological system, are naturally obliged to understand their impacts on the various components of the system. From a self-interest perspective, "humans manage ecosystems to minimize economic cost or maximize economic gain" [33]. Yet, there is a growing awareness that humans should also manage ecosystems out of moral concerns and affective interaction with other species. It leads to the analogy of humans as stewards of the Earth, implying that humans are obliged to care for and protect the ecosystems.

Closely related to or even derived from this type of moral concerns is the nascent field of environmental virtue ethics (EVE). It urges us to extend moral considerability beyond our own species and limit our conduct accordingly. The attention devoted to EVE can be traced back to early environmentalists including Arne Naess, Aldo Leopold, and Rachel Carson, who not only write about nature but also advocate lifestyles that reflect a greater understanding and respect to nature [40]. In EVE, respect, prudence, and practical wisdom, among others, are identified as prominent environmental virtues. Respect recognizes that human life is not separate from the environment and other forms of life have their own intrinsic value. Prudence builds on the importance of guiding our life according to enlightened self-interest rather than selfish and short-term gratification [41]. "Prudence is still self-interest, but it involves caution, social awareness and long-term thinking. [… It] leads us to decide what is good for us in particular circumstances" [42]. And this connects to practical wisdom, which "permeates the other two [above-mentioned environmental virtues]" [41] and advises us to care for "the integrity, stability, and beauty of the biotic community" [35].

In EVE, there is another noteworthy approach, which is derived from a variety of sources, such as conservation giants Henry David Thoreau, Aldo Leopold, and Rachel Carson. In *Thoreau, Leopold, and Carson: Toward an Environmental Virtue Ethics*, Philip Cafaro regards these three authors as environmental ethicists and interprets aspects of their works and lives [43]. For Thoreau, "simplicity" is a keystone value. "It plays an important role in stabilizing and focusing our lives [… and it] will be an important virtue for any environmental virtue ethics, for the obvious reason that living simply decreases our impact on other living things" [43]. Leopold writes about a formula for environmental conservation, which "urges only enlightened self-interest" [35]. "Enlightened self-interest" here is contrasted with a benighted, economism-based, and mistaken definition of self-interest [35]. Carson states that "man, however much he may like to pretend the contrary, is part of nature. [… He cannot] escape a pollution that is now so thoroughly distributed throughout the world" [44].

These authors are our conscience, rooting their beliefs in individuals' interactions with and ideas and feelings about other people, species, and ecosystems and acknowledging the interconnectedness between humans and the environment. Their exemplification of a high degree of environmental awareness once again consolidates the logics and the need of incorporating the ethical dimension into decision-making toward sustainability as proposed in this study.

When attempting to incorporate the ethical dimension into SA, guiding principles of a qualitative nature may prove to be more suitable than a set of fixed quantitative indicators because ethical concerns are more of aspirations rather than absolutes. Also, as principles are usually designed to be flexible enough to be adopted by different entities, they provide a good starting point for decision-makers on the journey toward sustainability, assisting government officials in understanding the implications of decisions taken at a broad strategic level [45].

An example of such guiding principles can be found through a careful observation of Thoreau, Leopold, and Carson's writings. These authors indeed share certain common positions [43], as summarized in *All about EVE: A Report on Environmental Virtue Ethics Today*, stipulating that we must [40, 43]:

- "Value material wealth as a means to providing people with a decent standard of living while acknowledging higher values than those implied by consumption and acquisition" [40].
- "Cultivate an understanding of the natural world and our own bioregion that privileges conservation over the exploitation of the natural world for profit" [40].
- "Approach environmental ethics from a non anthropocentric standpoint" [40].
- "Recognize that we benefit ourselves and enrich our own lives when we conserve wild nature, particularly through the moral lessons we learn from experiencing nature" [40].
- "Cultivate the bedrock belief that both human and nonhuman life is good, and this belief must be evident in our own responses to the natural world" [40].

2.4 Conclusion

Though the abovementioned EVE heavyweights vary in terms of their individual lives, they focus on kindred concerns of a distinctive ethical and qualitative nature. Relying solely on the extant three pillars of sustainability measured and represented in quantitative terms is not sufficient to constitute broad-gauge SA. As in the real life, a pillar can stand firmly only on a solid foundation. The three sustainability pillars should be rooted on "the triple foundation of human health considerations, the moral considerability of nonhuman beings, and the value to humans of preserving wild nature" [43]. The three pillars, seemingly incompatible because of the commonly perceived trade-offs of the environment for economic gains and social benefits, can now unite on such foundation. Materialistic losses in quantitative terms can be written off against moral gains in qualitative terms and vice versa. Only by incorporating the ethical dimension into SA can we take account of the full cost involved in human development and produce the real bottom line of our balance sheet of sustainability.

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Chapter 3
Development of an Environmental Management System Framework for Hong Kong Higher Education Institutions

Yi-Chen Lan and Shiu Chuen Lee

3.1 Background and Research Case

This research aims to develop an Environmental Management System Framework which is suitable for adoption by the higher education institutions (HEIs) in Hong Kong. There are eight publicly funded HEIs in Hong Kong, which are:

- City University of Hong Kong.
- Hong Kong Baptist University.
- Lingnan University.
- The Chinese University of Hong Kong.
- The Education University of Hong Kong.
- The Hong Kong Polytechnic University.
- The Hong Kong University of Science and Technology.
- University of Hong Kong.

Through their pivotal and influential role, the HEIs are the key stakeholders in implementing environmental policies set by the government, educating the society on the environmental responsibility, and achieving sustainable future [1, 2]. All the above HEIs in Hong Kong are engaged with environmental sustainability in their management and operation and have conducted a series of initiatives to ensure their campuses are environmentally sustainable. Some HEIs have obtained significant public recognition for their endeavours. Examples include winning the Gold Sectorial Award by the Chinese University of Hong Kong in 2013 [3] and winning the Silver Sectorial Award by Hong Kong Baptist University in 2011 [4], respectively, at the Hong Kong Awards for Environmental Excellence under the category of Public Organizations and Utilities. The eight HEIs have formed a Hong Kong Consortium for Campus Sustainability (HKCCS) to promote environmental

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sustainability on campus, and all these HEIs have signed a Hong Kong Declaration to that effect on 18 May 2010 which includes "a statement of principles regarding the importance of climate change and sustainable development for the universities…". The document further commits the signatories' institutions to reviewing their own campus operations; establishing targets for the reduction of energy consumption, greenhouse gas emissions, water use, and waste; incorporating relevant issues in the teaching curriculum; and reporting regularly on key environmental performance measures. Signing of the Hong Kong Declaration also formally establishes the HKCCS under the Heads of Universities Committee [5].

Except two functions of City University of Hong Kong, none of the HEIs or their units has adopted any formal Environmental Management System (EMS) for structuring its efforts in ensuring environmental sustainability on campus. According to the Directory of ISO 14001 Certified Companies in Hong Kong [6] published by the Environmental Protection Department of the Government of Hong Kong Special Administrative Region, as at the end of 2015, there were 939 entities which had obtained certifications for compliance with ISO 14001 (2004 version), being part of the ISO 14000 series of environmental standards developed by the International Organization for Standardization.

An EMS is defined as a system that compiles internal efforts at policymaking, assessment, planning, and implementation of environmental management [7, 8]. This research has involved a systematic analysis of the practices on environmental sustainability currently undertaken by the HEIs of Hong Kong based on the theoretical framework of Dynamic Capabilities and the use of the common sustainable practices under the Dynamic Capabilities and the requirements of ISO 14001:2015 (hereinafter ISO 14001) for comparison. The research has found out, as compared with the common sustainable practices under the Dynamic Capabilities and the requirements of ISO 14001, (a) what are not present in the practices of these HEIs (missing elements), (b) the practices which are not common sustainable practices under Dynamic Capabilities nor required by the ISO 14001 but being practised by any of the HEIs (additional elements), (c) the reasons for these practices, and (d) the views on importance of external certification.

The research has examined and documented the environmental sustainability measures of the eight HEIs of Hong Kong including the policy, structure, planning, reporting, and process. The common sustainable practices under the Dynamic Capabilities and the required elements of the ISO 14001 have been examined and matched with the environmental sustainability measures of the HEIs documented to identify the missing elements and additional elements.

This paper first introduces the interrelationship between Dynamic Capabilities and ISO 14001 and analyses their key features for ensuring environmental sustainability. In the stage 1 of the research, the practices of the eight HEIs are examined by review of their published information and confirmed with the officers by qualitative and semi-structured interviews. Thereafter the comparison of the practices of the eight HEIs and the key features in the Dynamic Capabilities and ISO 14001 is made with a view to developing initially an EMS framework for the HEIs. In the stage 2 of the research, the expectation of the staff and students, being the major stakeholders of HEIs, for the key features in the Dynamic Capabilities and ISO 14001 will be gauged by semi-structured interviews. After these interviews the EMS framework may be revised, which will meet the expectation of the stakeholders of the HEIs.

3.2 Interrelationship Between Dynamic Capability and ISO 14001

An EMS follows a plan-do-check-act cycle which is a structured way of ensuring effectiveness of measures undertaken by organisations [9]. There are many studies, which show that EMS is effective in companies in various industries such as oil, utility, pulp, paper, etc. [10–12]. There are a significant number of literatures, which demonstrate the effectiveness of using EMS in HEIs [9, 13–20].

This research has used Dynamic Capabilities as a theoretical framework to analyse the applicability of an EMS to organisations and in particular HEIs. The term Dynamic Capabilities was first introduced in a working paper in 1989, which was influenced by Gary Hamel's multinational strategy research, and was later used as an innovative strategic tool [21]. Dynamic Capabilities is defined by one study as the firm's processes that use resources to integrate, reconfigure, gain, and release resources to match and even create market change and thus are the organisational and strategic routines by which firms achieve new resource configuration as markets emerge, collide, split, evolve, and die [22]. Since 1989 there have been numerous studies on the topic of Dynamic Capabilities and Dynamic Capabilities View to organisations or firms. Studies on this topic were extended to strategic management by the work of Teece et al., which analysed the sources and methods of private enterprises in the creation of wealth and enhancing competitiveness in the environment of rapidly changing technologies [23]. In the recent years, the framework of Dynamic Capabilities has been extended to analyse how firms enhance their corporate social responsibilities (CSR), which include environmental sustainability. The applicability of Dynamic Capabilities to CSR and environmental sustainability includes the three capabilities, namely, scanning/monitoring capability, sensing/seizing capability, and reconfiguration capability. It is noted from these studies that the three capabilities are interrelated and overlapping [24]. A huge telecom company examined in one of the studies using Dynamic Capabilities View, when implementing CSR (which includes the responsibility for environmental sustainability), used the plan-do-check-act model [25]. This is the same model as that adopted by ISO 14001. As dynamic capabilities are considered as replicable routines [26] and exhibit commonalities across firms [22], the common sustainable practices adopted by firms under the three capabilities, scanning/monitoring capability, sensing/seizing capability, and reconfiguration capability, can be used as benchmarks for identifying whether there are gaps in the sustainable practices of the organisations and in this case the HEIs for environmental sustainability.

The common sustainable practices of firms under the three capabilities, in the context of environmental sustainability, include:

3.2.1 Sensing/Seizing Capability

- Designing a strategic plan to develop new sustainable initiatives.
- Keeping a formal governance structure to manage the broad research about the best practices regarding sustainability.
- Keeping dedicated teams to guide collaborative sustainability projects with stakeholders.
- Focusing on the development of practices and procedures that have a lower level of environmental impact.

3.2.2 Reconfiguration Capability

- Performing auditing and risk analysis about potential factors that cause environmental impacts.
- Periodically measuring the efficiency levels of the resources used.
- Implementation of a standard EMS such as ISO 14001.
- Managing external factors that cause negative sustainable impacts through collaboration with external business partners [24].

This research argues that although the implementation of a standard EMS is considered a common practice under the reconfiguration capacity using the Dynamic Capacities View, because of the interrelated and overlapping nature of the three capabilities, an effective EMS would permeate the three capabilities and building an appropriate and effective EMS could ensure covering these capabilities.

As noted above, there is significant number of literatures, which demonstrate the effectiveness of using EMS in HEIs. One study argues that some HEIs have implemented EMS to help them organise activities in order to recognise and reduce environmental effects [27]. Another study suggests that an effective EMS must be adopted so as to manage and assess HEI's impact on the environment [28].

An EMS would enable a HEI: "better regulation of responsibilities and better environmental performance documentation, reduced risk of regulatory breaches, cost reduction, improved personnel motivation and training, and better environmental communication…" [29]. In some countries there is an increasing trend that HEIs are using EMS for ensuring environmental sustainability [13, 15, 30].

Out of the various EMSs, ISO 14001 is the most common tool used in the private and public sector, including HEIs. According to a survey by ISO, in 2013, there were 285,000 ISO 14001 certifications produced worldwide [31]. Another EMS commonly used is the EU Eco-Management and Audit Scheme developed by the European Commission. There were 4500 organisations and 8150 sites approximately worldwide which adopted this system [32]. This is much less than that of the ISO 14001.

3.3 The Research Model, the Outcome, and the Framework Development

The design of this research has adopted a qualitative approach with semi-structured interviews for data collection and fact finding. Semi-structured interviews have been used to enable a series of predetermined but open-ended questions to be asked [33]. With the aid of a written interview guide for each stage of the study, the predetermined questions are set out. The research has followed the Maxwell's Interactive Model of Research Design [34].

The model of the research has followed the steps: (a) first examined the practices of the eight HEIs based on the published information; (b) conducted semi-structured interviews with the officers responsible for environmental sustainability (altogether nine interviews from eight HEIs) to verify and confirm the practices of the HEIs; and (c) used the following structure for the comparative analysis with Dynamic Capabilities and ISO 14001 requirements.

Structure adopted for the comparison with the features in the ISO 14001, to inquire into whether the HEIs have:

1. Leadership.
    (a) Leadership and commitment.
    (b) Environmental policy.
    (c) Clear organisational roles, responsibilities, and authorities.
2. Planning.
    (d) Actions to address risks and opportunities.
    (e) Set environmental objectives and planning to achieve.
3. Support.
    (f) Resources.
    (g) Competence of staff.
    (h) Awareness of staff.
    (i) Communication to/from stakeholders.
    (j) Documented information.
4. Operation.
    (k) Operational planning and control.
    (l) Emergency preparedness and response.

5. Performance evaluation.
    - (m) Monitoring, measurement, analysis, and evaluation.
    - (n) Internal audit.
    - (o) Management review.
6. Improvement process.
    - (p) Seek opportunities for improvement.
    - (q) Establish non-conformity and corrective action.
    - (r) Establish process for continual improvement.

Structure used for comparison with the features in the Dynamic Capabilities, to inquire into whether the HEIs have:

1. Formal and informal communication channel with stakeholders.
2. A knowledge base of new environmental information.
3. Developing new sustainable development strategies through public consultation.
4. A strategic plan, a formal governance structure, and a dedicated team to manage the process and develop new sustainable initiative.
5. Putting focus on the development of practices and procedures to ensure environmental sustainability.
6. Performing auditing and risk analysis about potential factors that cause environmental impacts.
7. Periodically measuring the efficiency levels of the resources used.
8. Collaborating with external business partners, e.g. caterers for ensuring environmental sustainability.

The study has compared the aforesaid features with the practices of the HEIs. The following paragraphs outline the comparison between the practices of the HEIs with those of the ISO 14001.

3.3.1 Leadership

It reflects that regarding leadership, seven out of eight HEIs have leadership and commitment from the top. According to the semi-structured interviews, only HE4 said there was not much focus and commitment on environmental sustainability from the top management. Some have longer history of ensuring environmental sustainability. One HEI started 15 years ago. Another one started to publicly announce that it was a low-carbon campus in the year 2009. All the HEIs have signed the Hong Kong Declaration [5]. All of them have formulated environmental policies, except one. The organisation for environmental sustainability varies from a formal office (three out of eight HEIs) to a designated team of staff taking up concurrent responsibilities for environmental sustainability (five out of eight). These five HEIs organise its efforts through their estates offices. Invariably all the staff members concerned of these eight HEIs understand and have a clear mandate for ensuring environmental sustainability.

3.3.2 Planning

As regards planning, the variation is found to be greater. Two out of eight (HE1 and HE2) have put in formal plans with specific targets for the initiatives. HE1 has a committee under the university governance, which does such planning. The officer of the HE1 said the committee plans, supports, and evaluates the efforts of HE1 in environmental sustainability. HE2 has a plan each year and budget for the activities, and before formulation of the next year plan, the results of the current year are evaluated. Five HEIs have the planning for ensuring environmental sustainability broadly covered in their university strategic plans or discussed in the strategic planning processes. HE4 has not got any explicit planning and target setting processes in place. Half of the HEIs, HE1, HE2, HE6, and HE8, have set targets and goals for environmental sustainability. The other four, HE3, HE4, HE5, and HE7, have not set targets. In the interview, the officer of HE3 said that HE3 was not keen on planning, so there were no specific targets. The officer of HE4 said the HE4 had not formulated any plan or targets for ensuring environmental sustainability although efforts in these endeavours were made.

3.3.3 Support

Resources are made available in all eight HEIs in the form of financial resources for building works and promotional work, but the adequacy of these resources varies. The officers from HE4 and HE6 expressed that resources available were not sufficient. On the other hand, HE2 allocates regular budget of HK$ one million every year for promotional work and activities involving staff and students. All eight HEIs have put in place communication channels to promote environmental sustainability and publicise the achievements on this front. All of these HEIs have staff members across the university community who are keen on environmental sustainability. Some of them are full-time staff whilst others have part-time staff members or staff members taking up the responsibilities for environmental sustainability on concurrent basis. All of the HEIs have obtained student body support for environmental sustainability, and there are many student activities such as appointing student ambassadors for promoting environmental sustainability, student outreach services to promote environmental sustainability to the public, study tour overseas, etc. conducted by these eight HEIs. The active engagement of students and staff members in environmental sustainability is a unique feature not covered in Dynamic Capabilities or ISO 14001.

3.3.4 Documentation

As regards documentation of the efforts made in environmental sustainability, all eight HEIs have materials on environmental sustainability in the form of communication with stakeholders on websites and publications and research output which are scattered around different units of the HEIs. As regards how deliberate the processes are, four HEIs have expressed that they did not have a structured way to document procedures and processes for environmental sustainability in a comprehensive manner.

3.3.5 Operational Procedures

All the HEIs have emergency preparedness for preventing physical risks including laboratory safety. However, five HEIs said there were no detailed operational procedures for ensuring environmental sustainability.

3.3.6 Performance Review and Seeking Improvement

As regards review of the efforts and achievements of environmental sustainability and improvement seeking, the variation is great which is similar to the variation in planning as explained above. HE1 has a setup in which the committee under the governance reviews its achievement on the targets planned on environmental sustainability and suggests improvement. This is also communicated to the university stakeholders including staff, students, and alumni. HE2 reviews its performance when formulating the plan for the next year. The rest of the HEIs (six) also communicate with their stakeholders on the achievements on the work and efforts on environmental sustainability but have not got a system of seeking feedback on improvement. All the HEIs have not got the internal audit engage in the studies on their efforts in ensuring environmental sustainability which is understandable as the internal audit in Hong Kong usually focuses on examination of internal controls and checks and balances, and not specific issues such as environmental sustainability.

The following table compares the practices of HEIs with the features of Dynamic Capabilities.

From the above, the HEIs have done most of the features as shown in the ISO 14001 and Dynamic Capabilities. The lesser done is on two aspects: planning, review, and improvement seeking and documentation, including setting up knowledge base, getting external certification, and establishing manuals. As EMS is defined as a collection of internal efforts at policymaking, assessment, planning, and implementation [7, 8], to implement an EMS, the first aspect, namely, planning, review, and improvement seeking, should be strengthened. As far as the second

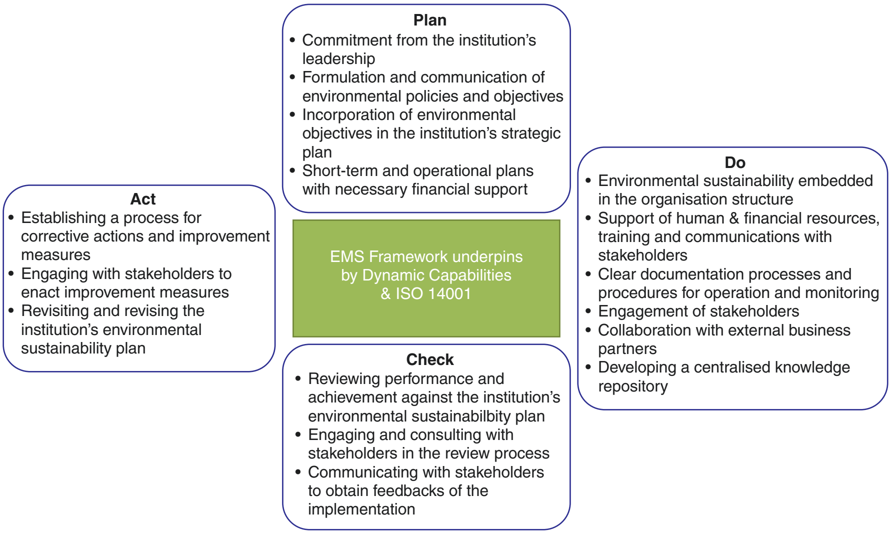

Fig. 3.1 Environmental management system framework for HEIs in Hong Kong

aspect is concerned, the nine officers of the HEIs interviewed do not consider getting external certification important. A statement made by the officer of HE2 typically reflects the views of all the HEI, which is not to get external certification solely for the sake of getting it. The HEIs also do not consider detailed and elaborate documentation including setting up detailed procedures and operation manuals necessary.

In the interviews, the officers responded that an EMS, which features the practices in the Dynamic Capabilities and ISO 14001 as described above with engagement of the stakeholders including students and staff, would be desirable. An EMS without external certification or detailed procedures and documentation but with stakeholder engagement would be a good way forward.

Based on the above findings and comparison with Dynamic Capabilities and ISO 14001 guidelines, an Environmental Management System Framework is proposed for adoption and forming an integral part of the strategic plan for the Hong Kong higher education sector.

Figure 3.1 illustrates the Environmental Management System Framework for the Hong Kong higher education sector. The EMS framework should be based on the plan-do-check-act which incorporates the key features in Dynamic Capabilities and ISO 14001 (Table 3.1).

3.3.7 Plan

1. Institution leadership and senior management to espouse its commitment to the environmental sustainability plan.

Table 3.1 Comparison of the current practices of HEIs with the features of Dynamic Capabilities

Key features in the Dynamic Capabilities	Summary of findings of the current practices of HEIs
Formal and informal communication channel with stakeholders	The study reflects that all HEIs have formal and informal communication channels with their stakeholders. But all of them do not engage the general public in consultations on the ways of ensuring environmental sustainability in setting their strategies
A knowledge base of new environmental information	All the HEIs do not have a formal knowledge base established. One HEI has formulated a campus sustainability guide [35]. However, this HEI has not got to the stage to put all measures, information, and procedures in environmental sustainability in the form of knowledge base
Developing new sustainable development strategies through public consultation	All the HEIs do not engage the general public in developing sustainable development strategies
A strategic plan, a formal governance structure, and a dedicated team to manage the process and develop new sustainable initiative	All of the HEIs have got their commitment and resources in environmental sustainability, but the practices vary in terms of planning, organisation structure, and staff resources to manage the process as described above in the section in comparison with ISO 14001
Put focus on the development of practices and procedures to ensure environmental sustainability	The HEIs have got their focus on the development of practices to ensure environmental sustainability and deploy resources to undertake the work
Performing auditing and risk analysis about potential factors that cause environmental impacts	All the HEIs do not engage their internal audit functions in auditing their efforts in ensuring environmental sustainability. See reason above in the section in comparison with ISO 14001
Periodically measuring the efficiency levels of the resources used	In terms of measuring the results on environmental sustainability, all HEIs do this which includes energy consumption, water consumption, and greenhouse emission. Four HEIs have expressed that they did the data collection and recording on a regular basis. Some do this on a more ad hoc basis
Collaborating with external business partners, e.g. caterers for ensuring environmental sustainability	Six of the HEIs engage the outside service providers and outside suppliers to arrange for measures to safeguard environmental sustainability. The remaining two are in the process of starting the collaboration with the outside parties

2. Environmental policy and objectives to be formulated and communicated.
3. Environmental objectives to be included in the long-term strategic plan which will be determined by engaging the stakeholders, including staff members and students through focus group meetings and/or open consultation sessions.
4. Short-term and operational plans such as annual plan and budget to be formulated.

The above items (1) and (2) are being practised by the majority of the HEIs, whereas items (3) and (4) will need to be strengthened when implementing an EMS.

3.3.8 Do

1. Clear organisation structure and scheme of authorities for ensuring environmental sustainability to be established.
2. Support to be in place for ensuring environmental sustainability including allocation of financial resources and manpower, providing training and development to staff members engaged in the work, and establishing and maintaining communication channels with stakeholders of the HEIs.
3. Set up of systematic operational and monitoring processes for the environmental sustainability.
4. Clear documentation on the EMS, including a set of procedures for the EMS, reporting mechanism and database for recording achievement in environmental sustainability to be established, without third-party certification.
5. Engagement of stakeholders including staff members and students in the activities for ensuring environmental sustainability.
6. Collaboration with external business partners, e.g. caterers and suppliers, for ensuring environmental sustainability.

The above items (1), (2), (5), and (6) are practices of the majority of the HEIs. Items (3) and (4) need to be established when implementing EMS.

3.3.9 Check

1. Management reviews of the activities and achievement against the institution's environmental sustainability plan.
2. Establishment of a centralised knowledge repository to capture the relevant information and knowledge.
3. Engagement of stakeholders including staff members and students in the review process by focus group meetings and/or open consultation sessions.
4. Broadening the engagement to the external stakeholders.
5. Communication with the stakeholders on the activities and achievement and seeking feedback.

All the above items need to be strengthened in conjunction with strengthening the planning of the HEIs, when implementing EMS.

3.3.10 Act

1. A process for corrective actions and improvement measures to be established.
2. Engagement of stakeholders including staff members and students in taking improvement measures by focus group meetings and/or open consultation sessions.

3. The institution's environmental sustainability plan is to be revised after the revision.

When implementing EMS, all the items need to be strengthened in conjunction with strengthening the planning and checking.

Overall, engagement of stakeholders including staff members and students is the unique feature in the above EMS framework.

3.4 Conclusion and the Next Stage

The gap between the practices of the HEIs on environmental sustainability and those practices featured in the Dynamic Capabilities and ISO 14001 is not significant. The development of an EMS, which includes the aforesaid features, is feasible. The HEIs are not on the other hand prepared to spend resources to obtain external certification and elaborate documentation. This has not been included in the EMS framework as described above. The EMS should include the participation of staff members and students in various processes in implication. Based on the comparison of the findings with Dynamic Capabilities and ISO 14001, an EMS framework is developed to illustrate the integrated plan in achieving environmental sustainable operation and present the holistic and comprehensive approach for Hong Kong higher education institutions.

In the next stage of this research, the expectation of the staff members and students for those practices featured in the Dynamic Capabilities and ISO 14001 would be gauged through semi-structured interviews. The qualitative data captured through the second-phase interviews will be used to validate and fine-tune the EMS framework. At the end of the stage 2, a suggested and tested EMS model with development specifications, which would be feasible for adoption to fulfil the expectation of stakeholders of the HEIs.

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Chapter 4
Exploring the Environmental Movement for the Preservation of Big Trees: A Case Study of Urban Areas in Thailand

Gwyntorn Satean

4.1 Introduction

In Thailand, a temple named “Wat Pak Ping Tawan Tok,” located in Ngiw Ngam Sub-district, Phitsanulok Province, is popular for a 40-year-old big elegant tree called a “Benjamin tree” (*Ficus benjamina*). The trunk of the tree is measured by about five adults fully holding hands to encircle the trunk, which is approximately 12.75 m. The tree reaches 9.75 m in height and is more than 10 m wide including branches. The distinctive features of the Benjamin tree include roots that firmly support the stalk. The root system drooping into the ground was once supported with bamboo and later grew into 26 large, minor trees, with an average diameter of 0.37 m each; the largest root measures 0.58 m in diameter [1]. Another temple, located in Wat Yang, Lopburi, contains a tree named “Yang” (*Dipterocarpus alatus*); aged about 300–400 years old, the trunk of which is measured by about 13 adults fully holding hands to encircle the trunk. With such distinctive features, it is valued for preservation by the community [2] (Fig. 4.1).

Apart from the aforementioned temples, large trees can be found surrounding official places, educational institutions, and forest areas. However, in urban areas or areas of infrastructure development, especially roads and facilities of urgent necessity for increasing the gross domestic product (GDP), big trees and ecosystem services have been devalued. Moonjinda [2] says that along footpaths in front of urban residences in the Bangkok metropolis, trees such as the Burmese rosewood (*Pterocarpus indicus*) have their tops cut and they look undersized with sparse leaves and barren bark. They rot away and curl up, and some are damaged, with hollows in the trunks. In addition, some have termite tracks and eventually die. It hardly resembles the mature trees with shading branches converged together along both sides of the road in places like Singapore, Japan, Vietnam, China, or Myanmar.

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Fig. 4.1 Benjamin tree at Wat Pak Ping Tawan Tok (left) [1] and Yang tree at Wat Yang (right) [2]

Evidence of accelerated development in the area is the “Nan tree tunnel” [3]. It became a public issue by March 2015 when the tree preservation group objected to cutting trees along the 15-km Nan-Tha Wang Pha Road and the four-lane extension construction, from 9 to 12 m, linking Nan-Thungchang through the Huai Kon Thai-Laos transit point, by the Department of Highways, Thailand. It was eventually concluded by a forum that the 800-m tunnel would be retained with safety improvements. However, the tunnel was involved in a harsh storm, and consequently, the trees toppled over in the way, causing electric interruption for 2 days in the districts of Tha Wang Pha, Pua, Chiang Klang, and Thung Chang in Nan Province. The tree tunnel was eventually demolished to prevent it from affecting the development project.

Professor Emeritus Boonkham, National Artist in Visual Arts (Landscape Architecture) [4], says that in addition to architecture and buildings, big trees help promote a beneficial image of a city. Big trees, in turn, may cause problems to a city; that is to say, trees touching the power lines may cause outages and impact on the stability of power systems. In addition, invasive and destructive roots on the ground or sidewalk, buildings, or walls, as well as the obstruction of drainage, can be harmful to public safety. For example, some residents in Bangkok were frightened over the news that a tree in Chidlom toppled over, flopping down on the electric poles that subsequently crashed onto motorcyclists, resulting in two people injured and one woman dead (Fig. 4.2). The incident sparked fear among urban dwellers, and many view these large trees as hazardous [5]. As they have been accused of causing

Fig. 4.2 Falling tree at Chidlom (left) [6] and incorrect pruning (right) [7]

damage, a lot of trees have been chopped down. Apart from reasons of fear and lack of understanding, Boonkham summarizes four main causes for the loss of big trees: (1) big trees are not valued by people and the responsible authorities in terms of ecological aesthetics and the environment, (2) people and the responsible authorities are not aware of the importance of caring for trees properly, (3) people and the responsible authorities lack urban tree management knowledge and application, and, lastly, (4) the applied principles of treating big trees are inappropriate for the function and use of trees.

However, even though big trees in cities have encountered threats, there has emerged an assembly of people through Facebook, leading to the formation of the “Big Trees Project” with an aim to raise awareness of the importance of big trees to the public. Online feedback is given to those authorities who are responsible for proper tree care, for instance, posting about big trees, inappropriate trimming, valuing big trees for conservation domestically and internationally, how to trim and prune trees properly, and other topics. In addition, it covers the activities of caring for big trees, for example, networking of volunteers caring for the tamarind trees surrounding Sanam Luang (Royal Field), and environmental movements by conservation groups for big trees. All of these have affected change in the management manipulated by government officials and in the way people think; that is, caring for big trees is not simply an activity undertaken by officers, but it involves public participation. Thus, it is an interesting social issue, especially in Thailand, where the experience of caring for big trees is still in the beginning stages as compared to

Singapore, where the former Prime Minister Lee Kuan Yew once set a vision of the city as the "Garden City" in 1967 [8].

4.2 Objective

This paper aims to examine the environmental movement led by the "Big Trees Project" in urban areas of Thailand, focusing on the discussion of the history, concepts, procedures, and social impact.

4.3 Methodology

A document-based research methodology was adopted during 2007–2017. Data was gathered from primary source documents related to big trees, urban forests, green spaces, arborists, and environmental movements, published articles in journals through *Thai Journals Online* (https://www.tci-thaijo.org), and the theses database from the Thailand Library Integrated System (http://tdc.thailis.or.th/tdc/) by the Office of the Higher Education Commission, including articles and interviews published in magazines, news and printed materials, online publications through websites, tape recordings aired on television, and social media such as Facebook Live and YouTube. In addition, the author participated in a training program for trimming and pruning big trees in urban landscapes organized by the Faculty of Architecture, Chulalongkorn University, together with the Big Trees Project as participatory observation toward environmental movement activities. Data analysis was then performed and presented in three scopes: (1) history, (2) concepts and procedures, and (3) social impact.

4.4 Results

4.4.1 History

The "Big Trees Project" was first initiated by a small group of six persons dwelling in the prime area of the Bangkok metropolis in May 2010. It was established through Facebook and Twitter, primarily aiming to conserve four to five giant rain trees (*Albizia saman*) and other large old trees surrounding Sukhumvit 35 Alley, Watthana District in Bangkok, which were being demolished for construction of a luxury shopping mall on a 60-hectare area [9, 10].

At the beginning, the Big Trees Project's activities were intended to conserve some giant rain trees, with branches over 30 m in height and aged over 200 years,

Fig. 4.3 An aerial view of the construction site from 2002 to 2016 [14–16]

as part of a green area to purify the air in this urban area. The images of the big trees were posted on social media under the topic “DO NOT WANT ‘GIANT TREES’ TO TOPPLE.” The term “Big Trees” was used until it was given attention by the media, leading to negotiation with the project owners on ways to conserve the big trees. Architectural specialists in designing commercial buildings were invited to participate. Next, fundraising was carried out, and more than one million baht was collected, and the Bangkok Metropolitan Administration (BMA) was assigned to dig up and relocate the giant trees to grow in a public park. However, the results of negotiation were not achieved as expected, because it was only a 5-day period before those relocated trees were cut down completely and the area became bare (Fig. 4.3). Consequently, the group decided to start a Facebook page called “Big Trees Projects” on November 2, 2010, for accessibility to the public. The page has been updated with occurring situations so that interested viewers can catch up. Initially, there were about 1,000 followers, and later, that grew to 9,000 followers in January 2011 [11, 12] and 142,000 followers by 2017 [13].

4.4.2 Concept and Procedures

The Big Trees Project presents its concepts through a variety of media from time to time, such as the Big Trees Project’s concept, “we do not make a story of big trees, but what matters for trees” [13]. Because of the declining number of big urban trees and natural forests, they believe that people and trees can coexist peacefully; humans gain benefits from trees. Thus, to find a way to live together in balance is a way to keep green spaces growing sustainably [17]. As urban people have still not recognized the importance of big trees, it is their effort then to persuade and engage the public to appreciate the value and importance of caring for big trees properly under urban tree management principles to preserve large trees and green spaces in urban and forest areas in a sustainable way. Therefore, the initial activities on Facebook page cover stimulating the public and society to be aware of natural resources. Intaaksorn, one of the founders, said nurturing an environmental consciousness is

Fig. 4.4 Reporting a tree incident [19]

not easy in the era of globalization, but when it materializes, humans will live in more harmony with their environment [18].

The Big Trees Project activities include dissemination of proper trimming and pruning techniques, publishing and sharing big tree photos that are perceived valuable to the community or ecosystems both domestically and internationally, persuading the public to take pictures of big trees from different places to be published, watching out for inappropriate tree cutting by government agencies (by posting the events relating to big trees on social media using the hashtag #tree patrol officer to report the incident) (Fig. 4.4) [19], and giving an ear via Facebook Live. These activities can be partaken in by the public regardless of who they are; they don't need to be an environmentalist, and it requires almost effortless participation, with no need for any organizers, skills, knowledge, and experience in forestry or protesting. They can join by just posting and sharing environmental care activities.

Anonymous, one of the founders, said that when initially launching a campaign for the conservation of giant rain trees, there were thousands of subscribers following daily on Facebook and there were so many comments and opinions posted that it was necessary for the *admin* to delete harsh messages that may cause anger and hatred. Their objective is to encourage people to recognize the value of beautiful, shade trees, not to provoke violence [11].

Later, although the Big Trees Project failed to sustain the protection of the giant rain trees, with the dissemination of the big tree stories, people and agencies began to pay attention, especially to those large trees under the supervision of the BMA, which have had roots or branches carelessly lopped off [20, 21], affecting the growth of the trees. Therefore, the "Thailand Urban Tree Network" Facebook page was set up to monitor and disseminate knowledge and give advice on how to trim and prune trees properly. The focus area was primarily Bangkok but expanded to other regions, as well as to plants in forest areas. Currently, there are 75 organizations and individuals in the group, including NGOs, academics, and media, for instance, Thammasat University, Somdet Chaopraya Institute of Psychiatry, PPTV Thailand, *A Day Magazine*, and Bird Conservation Society of Thailand [22]. In addition to simple and uncomplicated activities through social media, both groups have worked together to persuade the followers and public to join field activities, including cycling; sailing to survey big trees; a photo contest, together with the "Bangkok Big Tree" project [23]; and exhibitions such as the "Love Heritage Tree Project" [24]. Other activities include subscribing for training seminars on tree trimming and pruning through the Urban Tree Care School to create arborists [25] as volunteers to take care of the tamarind trees (*Tamarindus indica*) around Sanam Luang. This is a synergy between the Big Trees Project, the BMA, and the Royal Forest Department [26]. These activities are intended to raise awareness about participation in nature preservation.

Apart from the aforementioned activities, the Big Trees Project implemented the "Bangkok Greenbelt" policy to ensure adequate green spaces consistent with the number of the population. Currently, Bangkok has 12 parks, totaling 593.92 hectares in area. Green spaces averaged 3 m^2 per person, while the standard green spaces per capita are 16 m^2 [27]. The ultimate national-level goal is to push the government to enact big tree protection laws [12]. In Thailand, the big tree protection law prohibits illegal cutting, chopping, sawing, digging, and dragging of trees. Recently, it has been amended by the National Council for Peace and Order (NCPO) pursuant to Directive No. 31/2016 on the amendment of the forestry law to prevent, restrain, and suppress illegal cutting of trees, but this covers only economically valued trees such as teak, rosewood, blackwood, and Yang [28].

Yamarat, one of the founders, said that the urban large tree protection law is necessary. Such laws have long existed in foreign countries such as Germany, Singapore, Korea, and Taiwan. Its syllabus contains tree protection, arborists, and city plans to determine the green spaces appropriate to the population density and the punishment for those cutting trees, determined by the impact on air quality [12].

4.4.3 Social Impact

Over the past few years, Thai people have been more aware of big tree problems, especially regarding arboriculture which has been executed by some in the government sector improperly. Evidently, it has increased the amount of followers to over a hundred thousand for the Big Trees Project through the Facebook page, like other pages in the environmental scope of work, for example, WWF-Thailand (143,513 follows) [29], Greenpeace Thailand (310,917 follows) [30], and Seub Nakhasathien Foundation (189,051 follows) [31]. However, the activities the followers perceive through social media contribute to the conservation of big trees and green spaces and the restoration of nature successfully covering urban, suburban, and rural forest areas.

Fig. 4.5 Reforestation activity in Chiang Dao [34]

- Urban areas—it provides theoretical and practical knowledge of arboriculture to interested people. Currently, there are 217 members attending the fifth and sixth arboricultural training program at the Faculty of Architecture, Chulalongkorn University. A lot of participants are working in the field of landscape architecture, both for private and government agencies. No background knowledge is required, and everyone is welcome [32].
- Suburban areas—it induces public participation and awareness of the local people and the public about the conservation of 16 km^2 of Bang Krachao, which is considered “Bangkok’s last tropical sanctuary and Green Lung” [33], through activities such as “Biking, Planting, Nipa palm.”
- Other local areas—a reforestation campaign at the youth camp in Ping Watershed, Doi Luang Chiang Dao, Chiang Mai Province (Fig. 4.5) [34], funded by urban conservation groups, Big Trees Project and Greenpeace (Thailand), as well as a forum where respected conservationists and experts shared knowledge about ecology. More than 500 participants joined the activities, exceeding the 300 targeted participants [35].

Even though the social impact of such activities is small, it plants the seeds of conservation and care for big trees extensively. Some other activities carried out at the individual level include growing 800 plants carried out by Phonamnuai, an explorer, musician, and local tree planting activist, in Chiang Mai on August 21, 2015 [36], or growing three million trees by 1988 carried out by a volunteer, Pol Sublieutenant Wichai Suriyut [37]. These publicized environmental activities have inspired the young generation.

The strategic impact at the national level of caring for big trees occurred when the government set up the national 20-year environmental strategy. In particular, Prime Minister General Prayut Chan-o-cha instructed that arborists ought to be assigned to take care of the trees in public places in accordance with arboriculture principles [38, 39]. The result is that the Ministry of Natural Resources and Environment, Ministry of Interior, and other public sectors involved have to support the arborists to care for big trees and create a network at the community level [40]. Meanwhile, other agencies, such as the Metropolitan Electricity Authority (MEA), launched a workshop, “Tree Pruning Near Power Lines,” to provide knowledge on how to properly prune the branches for safety and the environment [41]. Likewise, the Bank of Thailand (BOT) announced at the BOT GO Green Exhibition that it would provide a permanent post of arborist at the bank to look after the bank's old trees [42].

4.5 Summary

On August 2014, *A Day Magazine* published an article entitled "Tree Planter" [17], citing overall tree problems in Thailand from 1824 to 2014, showing that the environmental movement emerged for the first time during 1990–2000 after the demise of Nakhasathien, the great protector of Thailand's natural resources. This leads to the establishment of the Seub Nakhasathien Foundation and later the forests of Thung Yai and Huai Kha Khaeng Wildlife Sanctuary, which were listed as UNESCO World Heritage sites in 1991 [43]. This was unlike the case of the Big Trees Project which resulted from the loss of giant rain trees and inappropriate pruning of urban trees by government agencies. Big Trees Project's concept is "do not make a story of big trees, but what matters for trees," especially urban trees which have encountered the stress of weather, highly compacted soil, long-duration flooding [44], improper maintenance, streetlights at night, and growth without an adequate support system from their neighbors. Wohlleben [45] said that "urban trees are the street kids of the forest, and they are like orphans."

Apart from the physical factors like the urban setting, most urban trees have been neglected by the public, but they have perceived that it is under the responsibility of the government sector. In addition, the people have no sense of belonging or involvement with trees [46]. Suthammakit et al. [47] mentioned that Bangkok people simply perceived that trees are important but did not make sense of what the urban forest is and were unwilling to pay for tree maintenance costs, except for donation for urban forests which is derived from the purchase of goods. Public agencies must educate the public, and at the same time, a specific organization should be set up to be responsible for long-term care of trees. The Big Trees Project functions contribute to environmental networking, government and private agencies, media, and educational institutions via activities on the Facebook page to create public awareness and educate them about big tree conservation.

Over the past 7 years, the Big Trees Project' s concept and approaches to tree conservation have had a substantial social and strategic impact through the Prime Minister's directives, mandating that all provinces shall have a number of arborists to oversee large trees. However, under its continuous administration, the ultimate goal is to encourage the government to enact bylaws governing the protection of large trees as well as arborists. They should examine the lessons from Singapore, a country governing under the Parks and Trees Act since 2005 [48] and the establishment of the Center for Urban Greenery and Ecology (CUGE) through the ISA

Certified Arborist Preparatory Programme and registered arborists, which currently has 525 members [49] caring for two million trees planted along roadsides and in parks, as well as protected natural resources [50].

Sookkamnerd, an economics scholar [51], stated that the overall environmental movement in Thailand could be divided into three stages, as in some Western countries, including (1) claiming or protesting development projects that may affect natural resources and the environment, (2) NGOs performing as thought leaders and proposing innovations for natural resources and environmental protection, and (3) national development with regard to mainstream environmental issues. Thailand is still in the first stage. To pass this stage, it should be equipped with (1) academic strength regarding the environment, (2) legal changes, and (3) public awareness of the environment. In the case of the environmental movement by the Big Trees Project and the Urban Tree Network, it could be summarized that it is in the second stage, as they are "innovators" in caring for urban trees.

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Chapter 5
Residents' Reactions Against Renewable Energy Facilities and Influence of Willingness of Investment

Nozomu Mishima, Kazuki Abe, and Toru Saito

5.1 Introduction

Renewable energy is, of course, a commonly agreed energy source in focusing on sustainable development. Especially in Japan, it has been strongly focused after the accident at Fukushima nuclear plant. The northeast area of Japan has high potential of wind energy. Thus, local government in the district is trying to introduce wind turbines and to boost related industries, such as manufacturing of equipment, maintenance, investment on wind farms, and retailing of electricity, which can boost local economy. However, in constructing such renewable energy facilities, always people's reaction called NIMBY (not in my backyard) [1–3] is the largest barrier. Although people think renewable energy is the best way toward sustainability, they do not want the facilities near their residential area. This unbalanced feeling between residents and nonresidents may be the highest barrier of promotion of renewable energy.

In our preceding study, personal feelings against nearby wind turbines were investigated. And the result told us that ownership or investment may affect residents' reaction against wind turbines. Especially, the bad feeling against "low-frequency vibration" evidently decreased by assuming that the respondent has an ownership of the wind turbines. This fact can be an important hint to promote implementation of wind turbines. In this study, new investigations at the wind turbines sites and data analyses were carried out. Five general problems of wind turbines, "noise," "accident," "low-frequency vibration," "damage to forest ecosystem," and "disturbance of landscape," were the focus of the investigation. Through the questionnaire, weights of the five problems in respondents' feeling were investigated. The results showed which of the five problems is the most critical problem for respondents. The analysis also compared residents' answers with visitors' (university

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students') answers, workers of the facility with residents, and those who have an intention of investment and don't have such intention. In general, visitors focus on environmental issues rather than personal influences. Facility workers focus on non-operation situation due to accidents. Respondents who have willingness of investment focus on both accidents and personal influences almost equally. These results suggested that by focusing on a certain problem, the negative feeling of residents to wind turbines can be solved. It also showed investment to wind turbines plays important roles. If a proper business model can be provided, it will be helpful in promoting installation of wind turbines. Finally, this kind of effort can be a solution of NIMBY problem and will be a small but important step toward sustainable future.

5.2 Effect of Ownership on Residents' Reactions

5.2.1 Investigation in Rokkasho-mura

Generally speaking, it is said that there are some mental barriers in installing wind turbines in the neighborhood. To know the actual perception against wind turbines, a questionnaire has been carried out in Rokkasho-mura, Aomori Prefecture. Since the village used to have some facilities regarding nuclear energy and a storage site of oil too, the village is one of the very important sites in energy policy of Japan. And now, they are steering toward renewable energy. Thus, it is significant to ask such questions regarding installation of wind turbines. In Rokkasho-mura, there are three companies trying to install wind turbines to local communities. Perception of people is always the key factor to determine whether the installation will be successful. In order to know the people's concern more clearly, a questionnaire was carried out. The questionnaire was carried out to 50 people. It provided several questions to ask their willingness/challenging feelings regarding five major problems in wind turbines. The focused five problems were "destruction of nature," "bird strike," "disturbance of landscape," "noise," and "low-frequency vibration."

5.2.2 Results of the Questionnaire

The previous survey results [4] shown in Fig. 5.1 told us ownership can be a key in promoting installation of wind turbines, since it eases negative feelings to "low-frequency vibration" which is difficult to quantify and to consider theoretical countermeasures. By asking "if you have some percentage of ownership in the nearby wind turbines, are these problems important for you?" On the other hand, in some factors such as "disturbance of landscape" and "bird strike," people think the facts are more problematic. This result suggested that ownership (investment) can be the key. But, at the same time, different countermeasures are necessary for different problems.

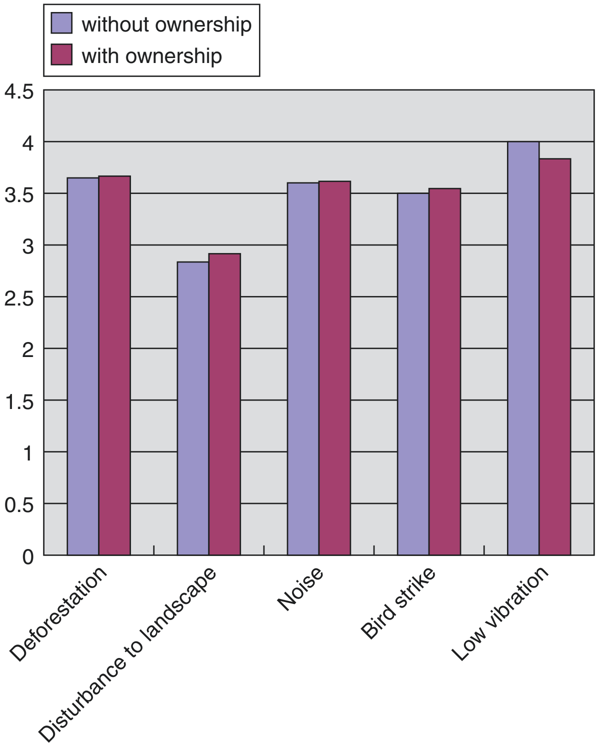


Fig. 5.1 Challenges of wind turbines for residents with/without ownership

5.3 New Surveys at Wind Turbine Sites

5.3.1 Focused Problems

In the new surveys [5], target problems were changed a little. According to "the guideline of environmental assessment on the construction of wind turbines [6]" which is provided by NEDO [7], we have determined these five problems as the target items of the investigations.

5.3.1.1 Destruction of Landscape

This is one of the simple but well-known problems in wind power installation. If the distance from the residential area to the wind turbine is close, there will be a mental pressure. In addition, sometimes the wind turbine itself damages the landscape. Recent wind turbine diameters are often larger than the length of a large airplane. Therefore, a wide pathway to bring in the turbine blade is necessary. This might cause a large-scale forest felling. Especially in Japan, where wind turbines are often built in mountain ranges, this could be a problem. However, whether people feel uncomfortable to see wind turbines depends on the case.

5.3.1.2 Damage on Ecosystem

Installation and operation of wind turbines can damage the ecosystem. As it is mentioned in the former section, if a forest felling occurs, some natural species might damage habitats. Bird strikes are sometimes reported. Although it varies due to bird species and weather conditions, it is said that peninsulas, capes, ridges, valleys, and sea cliffs are the locations where bird strikes can frequently occur. This fact also means that wind turbines are often located in these topographies.

5.3.1.3 Noise

This is one of the largest problems in wind turbines. Noises from wind turbines are from mechanical effects or hydrodynamic effects. The first one can be controlled by normal noise-controlling technologies and is not a dominant factor in recent wind power systems. However, the second one is sometimes inevitable and could be a serious problem in residential area. If there is a sufficient distance from the wind turbines, disturbance of conversation, damage to listening capability, and disturbance on work will not happen. But, some people may still feel annoyance or disturbance on sleep.

5.3.1.4 Low-Frequency Vibration

It was explained that noises from wind turbine have mechanical or hydrodynamic reasons. The first one sometimes has a wide frequency range from super low range to hearable frequency. And the super low-frequency noise is said to be the reason of low-frequency vibration. However, this kind of vibration exists in natural background, and theoretically this level of noise cannot affect people's health. But still many people around wind turbines claim that they feel low-frequency vibration. Without any clear theoretical backgrounds and countermeasures, this problem can be serious in persuading residential people on the installation of wind turbines [5].

5.3.1.5 Accident

After some 20 years, experiences of installations of commercial-level wind turbines in Japan, falling of parts from wind turbines because of thunderbolts and inadequate maintenances, happened rather frequently these years. Such accidents happened six times only in November and December of 2014. It exceeded the number of accidents in 2013. In March 2013, it was found that the whole rotor blade which has

Fig. 5.2 Serious accident in a wind turbine

50 m diameter fell on the ground (Fig. 5.2, [8]). The reasons of some of the accidents were design errors and inadequate maintenance processes. But sometimes, natural weather conditions such as thunderbolts and hurricanes cause the accident. These accidents can be a serious disaster if the wind turbines are located in residential areas.

5.3.2 Visitors' Perceptions

The purpose of carrying out the same questionnaire to students and to residents of the area is to clarify how perceptions against wind turbines are different with residents and visitors. So, since among 77 students respondents, seven answered that they live (or their parents live) near wind turbines, these seven respondents were categorized to residents. Other 70 students are representatives of visitors. Figure 5.3 shows the results of the investigation to students. Vertical axis shows the relative importance of five problems. As the length of the bar shows, "accidents" is the most serious problem. "Destruction of ecosystem" is the second largest problem for students.

5.3.3 Residents' Perceptions

To compare the acceptances against five major problems in installing wind power system, the same questionnaire was asked to residents in the aforementioned area. Since the area has not a high population density, the number of respondents was smaller than student respondents. We could collect 30 answers from 12 households. Seven answers from students who live near wind turbines were added to this category. The result shown in Fig. 5.4 indicates the same result about the top concern. Relative importance of "accidents" was the highest.

Fig. 5.3 Relative weight of visitors' challenges against wind turbines

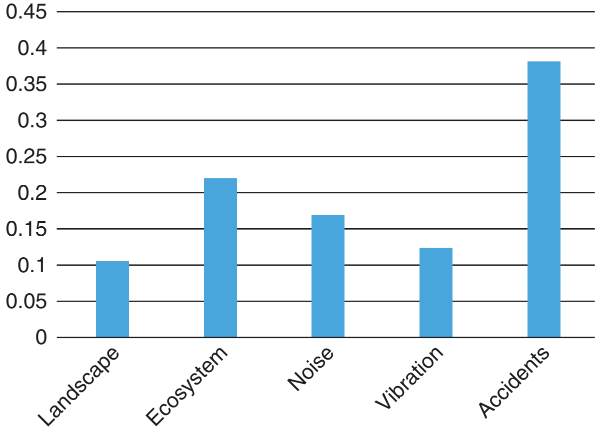
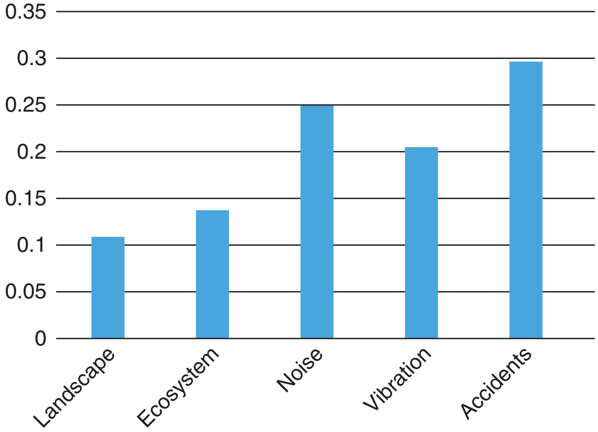


Fig. 5.4 Relative weight of residents' challenges of wind turbines



5.3.4 Comparison and Discussions

Important issues in considering acceptance of wind turbines are not only the relative importance of the problems but also the differences in perceptions of visitors (students) and residents. Table 5.1 shows the comparison between average of visitors' answers and that of residents.

Comparing both answers, it can be found that the problem with highest importance and lowest importance are the same. Basically, people are very anxious about accidents, visitors or residents whichever. In addition, not many people think the landscapes with wind turbines are uncomfortable. This fact can be a driving force to install wind power system to local communities. If other problems can be solved by technical countermeasures, installation of the wind turbines can be acceptable for residents also.

On the other hand, the largest differences in both answers are the order of the second through fourth. In visitors' answer, "damage on ecosystem" is a rather large

Table 5.1 Comparison on relative importance of five problems in visitors' and residents' answers

Order of importance	Visitors' answer	Residents' answers
1	Accidents	Accidents
2	Damage on ecosystem	Noise
3	Noise	Low-frequency vibration
4	Low-frequency vibration	Damage to ecosystem
5	Destruction of landscape	Destruction of landscape

concern. Since environmental education is common in Japanese junior high schools and senior high schools, university students may think damage to wild nature as a big problem. However, residents don't think this problem is really important. For residents, "noise" or "low-frequency vibration" which might affect daily lives is much more important than ideal problems such as "damage to ecosystem." These results suggest that different strategies are necessary in order to construct wind turbines close to residential area and to ask for nationwide investment on the wind turbines.

5.4 Relation Between Willingness of Investment

5.4.1 Residents' Case

Aforementioned result shows that perception to wind turbines of residents and visitors are rather different. To reduce negative reaction of residents and promote introduction of wind turbines to local communities, a different strategy will be necessary. In order to clarify deviation of residents' perception according to the increase of willingness of investment, feelings were investigated. A questionnaire using pair comparison method was carried out with an additional question to ask willingness of investment. Figure 5.5 shows the relative weight of five major challenges of wind turbines as for residents, compared by those who have some intention to invest versus those who have no intention. And Fig. 5.6 shows the same survey and comparison for visitors.

Then, in order to know a more detailed relation between intention of investment and maximum amount of money with perceptions against wind turbines, a cluster analysis categorizing the five major problems into three categories was used. For example, if the respondent weighs accidents much, the point will be close to the top corner of the triangle. Figure 5.7 shows what are the concerned problems among five major challenges of wind turbines, for those who have no intention of investment. On the other hand, Fig. 5.8 shows the answer to the same question by those who are interested in investing some amount of money.

The important finding from the survey is that the center of gravity of the answers shifts from about the center of the triangles toward the left upper direction as shown in Fig. 5.8. This means that when residents have some intention to invest on a

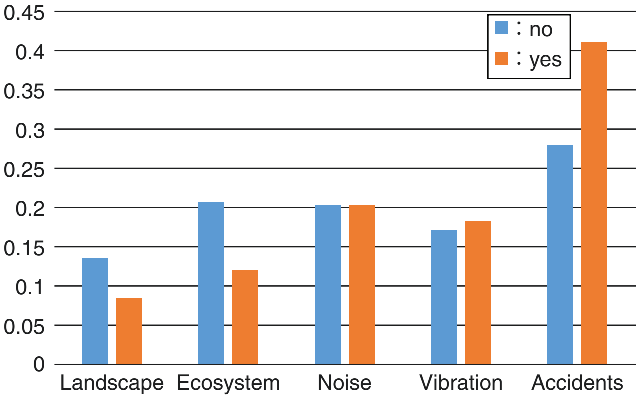


Fig. 5.5 Comparison of weight of five major problems of wind turbines based on willingness of investment

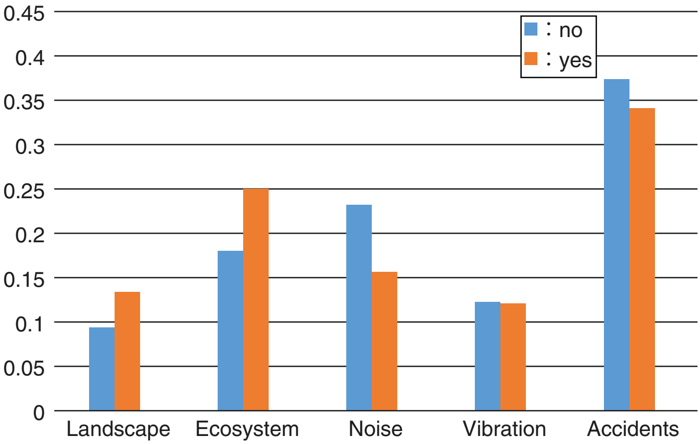


Fig. 5.6 Comparison of weights of five major problems for visitors of wind turbines based on willingness of investment

nearby wind power system, accidents, noise, and low-frequency vibration will be much bigger concerns than landscape destruction and damage to natural environment.

5.4.2 Visitors' Case

Another survey to nonresidents has been carried out also. Contrary to the residents' case, the center of the gravity of the answers moved to the opposite direction toward the right lower corner of the triangle, which means destruction of landscape and

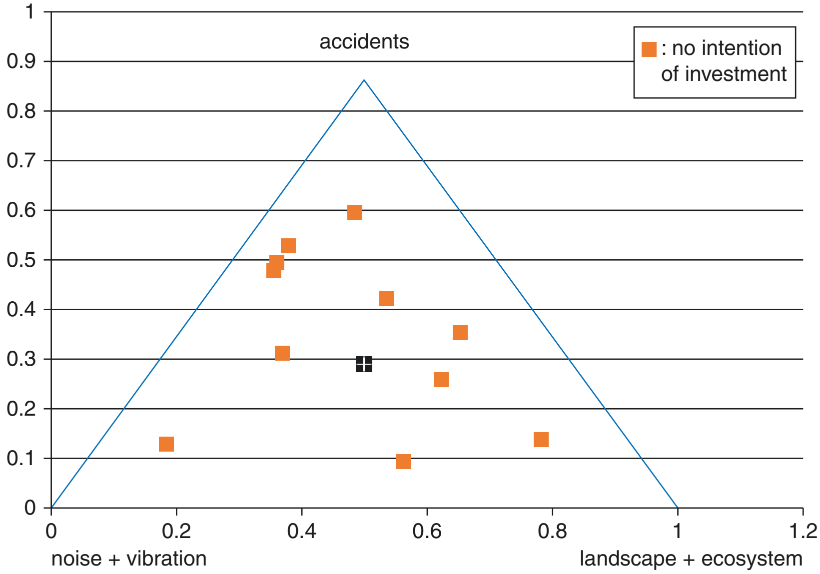


Fig. 5.7 Cluster analysis on the preception of residents without intention to invest

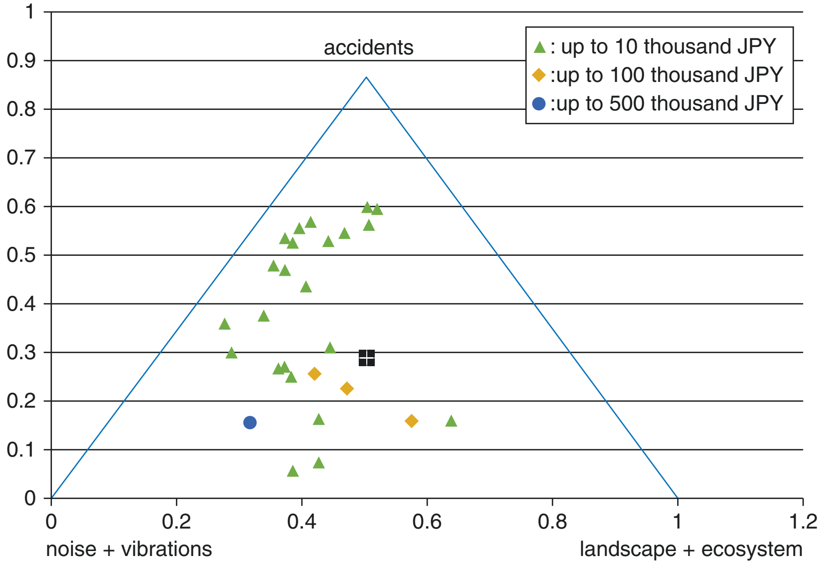


Fig. 5.8 Perception of residents with intention of investment

damage to natural environment are the increasing concern with the increase of willingness of investment. Figure 5.9 shows the result of those who have no intention to invest at all; Fig. 5.10 shows the same result of those who have some intention to invest.

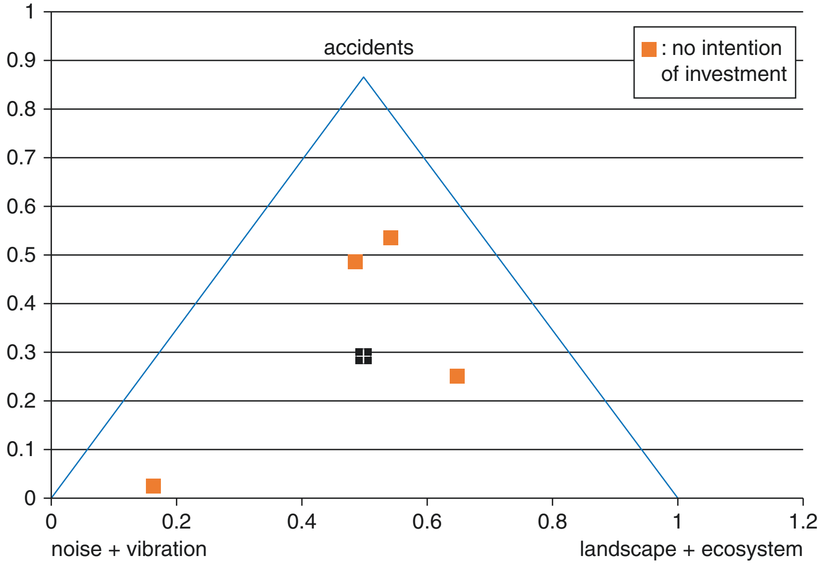


Fig. 5.9 Perception of visitors who have no intention of investment

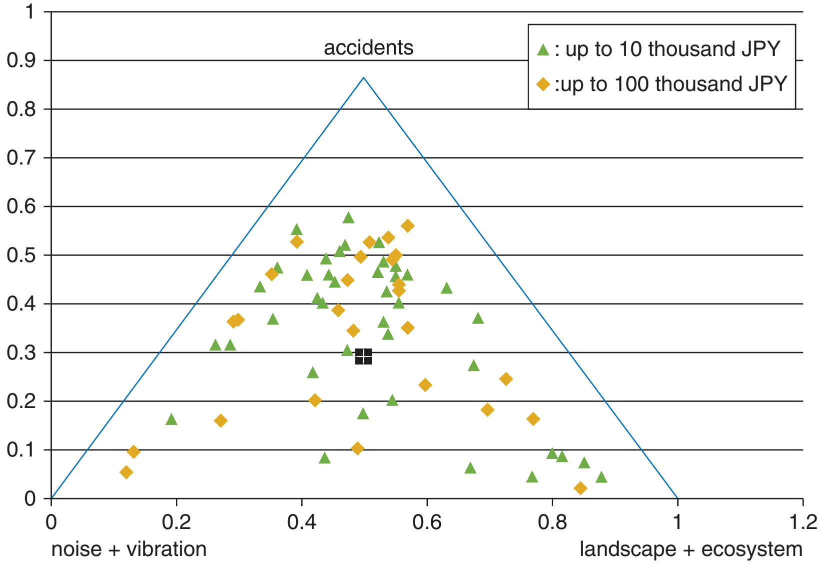


Fig. 5.10 Perception of visitors who have some intention to invest

5.4.3 Discussion

The survey results showed that private effects that are "noise" and "low-frequency vibration" are more concerned when the residents have some intention to invest. However, visitors' case is totally different. When the person has intention to invest on the wind turbine, he thinks public effects that are "destruction of landscape" and "damage to ecosystem" can be more important. It is supposed that residents tend to think *we* are the people affected by the wind turbines most of all.

Because of these facts, the strategy to install wind turbines around residential area and the strategy to ask for wide investment by cloud funding should be totally different. In conventional assessment procedure, it is required to explain all the possible effects to residents. However, the result suggests that the explanation should put emphasis on personal affections more. On the other hand, when the projects would like to get nationwide funding, the effect of the wind firm on natural environment should be explained seriously. The funders may want a certificate that their project is free from landscape destruction and a serious damage to ecosystem. The explanation should be with scientific knowledge to certify such problems are not so critical. It is significant that the study could quantify the effect of willingness of investment on the people's perceptions.

5.5 Summary

The paper focused on residents' perceptions in order to promote installation of wind power systems by asking which of the five major challenges of wind turbines are the biggest concerns. In addition, the deviation of the answers according to the increase of amount of money that the respondents intend to invest on the wind turbine was surveyed. The same survey was carried out to nonresidents. The result showed that different business models and different strategies are necessary to explain the safety of the wind turbines to residents and to ask for nationwide investment. The fact can be an important suggestion to promote the implementation of wind power which is one of the promising ways of renewable energy.

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Chapter 6
Sustainable Integration in Industrial Design Education: A Case Study of Japanese Universities

Edilson Shindi Ueda

6.1 Introduction

The main title of this study is part of a series related to design education for sustainability (DES), which has the main objective of disseminating and promoting design education in a sustainable context in the academic and professional fields.

DES has become increasingly prominent in recent years, with 2005–2014 being designated as the “Decade of Education for Sustainable Development” [1]. This trend has been reflected in industrial and product design education worldwide, and a study by [2] shows that over half of the 221 universities they surveyed stated that sustainable design considerations were compulsory on their courses, while a further 37% stated they were optional.

According to the experts [3], the industrial design field can offer a substantial opportunity to integrate sustainability and ecodesign approaches, which industrial design courses can be perceived as the most activity to date education in terms of sustainability. Toward those facts, the purpose of this study is to identify and to describe the numbers of current Japanese universities that offer undergraduate and graduate courses with sustainability and ecodesign modules. A number of questions related to DES are discussed in this research. The proposal theme and case study are beneficial for future reference of literature and also the broader remit of stakeholders, including teachers, researchers, and students.

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6.2 The Activities of Sustainable Development in the Academic Fields in Japanese Universities

Before introducing the academic studies on industrial design field, this section presents an overview of the sustainable education activities in Japan.

According to the Japanese Ministry of the Environment, Japan has stressed and encouraged the importance of integrating activities, events, and environmental concerns in educational program in order to achieve the goal of a sustainable society [4]. At the same time, the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) has developed a program called "Education for Sustainable Consumption (ESC)," within the environmental education and consumer education, targeting both school education and adult education [4].

In formal education, the National Curriculum Guidelines [5] establish the implementation of environmental education in elementary and middle school science, social studies, period for integrated learning, etc.

The Institute for Global Environmental Strategies (IGES) of Japan also has developed an education program for sustainable consumption, in which it has been taking place the consumer education as part of high school home economics. However, the IGES express that the number of hours allotted to these various modules is extremely limited [4].

From the experts' viewpoint [6], the Japanese higher education with Education for Sustainable Development (ESD) program has not yet adequately expanded, and at present it lacks the coherence of other educational reforms and would benefit from links with local schools. They also suggest that there is a lack of internal consensus to promote ESD and shared recognition inside universities, combined with a lack of effective guidance designed to enable students to acquire cross-disciplinary perspectives. Toward those facts, they have suggested encouraging leadership, teachers, lectures and researchers development for sustainability. They also reinforce that among universities, executive staff members and teachers are critical to continuing and strengthening efforts in this area in Japanese higher education.

6.3 The Literature of Industrial Design Education for Sustainability in Japanese Universities

Based on previous research [7], Japanese universities with industrial design education courses have incorporated a more traditional product design curriculum. Those studies were focused on the overview of traditional industrial design programs, based on a general design-related study of form and a presentation-, practical-, kansei-, ergonomics-, product-, and concept-related approach. Unfortunately, there is no evidence of any study related to the integration of ecodesign and sustainability considerations in Japanese industrial design education. Furthermore, there are no references on how education should deal with the issues of ecodesign and sustainable design specifically in the context of the education of undergraduate and postgraduate students. This fact is confirmed in papers published between 1999 and 2013 by the International Symposium on Eco-Design [8] and between 1997 and 2011 by the Special Issues of the Japanese Society for the Science of Design (JSSD) [9]. There is a small amount of historical data on the integration of sustainability into the design curriculum [10].

6.4 Research Objectives

As described in Sect. 6.3, an appropriate collection of references from current Japanese universities with ecodesign and sustainable design in their industrial design course appears to be lacking. In order to evidence and clarify the current ecodesign and sustainable design consideration in design education in Japan, this research identified the following questions (pertaining to the program and characteristics of each university with a product design program with environmental aspects):

Question 1. How can the Japanese universities characterize undergraduate courses in industrial design that have integrated ecodesign and sustainability into product design course?

Question 2. How can Japanese universities characterize postgraduate courses in industrial design that have integrated ecodesign and sustainability into product design course?

6.5 Research Methods

Initially, 118 Japanese universities with industrial design programs were identified through the guides [11–13] and brochures of faculties and departments of industrial design. In the second phase, universities that offer specialized courses in product design were identified. In the third phase, the selected universities were studied in detail, which included identifying programs and modules with theoretical and practical approaches to content on products with sustainability, ecodesign, and environmental awareness.

In order to facilitate the search for courses with a focus on sustainable design, the following terms were used: “green design,” “design for environment,” “ecodesign,” and “sustainable design.” Consultations with administrators, modules leaders, and lecturers of industrial design programs were also conducted in the respective universities.

A list of names and courses of Japanese universities in the second phase of the research is presented in Tables 6.1 and 6.2. The data were collected from April 2015

Table 6.1 Overview of Japanese product design course with sustainability consideration

(S)	Universities	(a) Categories of Universities	(b) Design Categories	(c) Design Degree (Bachelor)	(d) Modules Sustainability (Undergraduate)	(e) Master Doctor Program	(f) Modules Sustainability (Postgraduate)	(g) SD not officially integrated
1	Chiba University	◐	▲	❐	×	☆★	⊙	n/a
2	Tokyo University ot the Art	◐	⌓	❐	×	☆★	×	×
3	Kyushu University	◐	⌓	❐	×	☆★	×	×
4	Kyoto Institute of Technology	◐	▲	❐	×	☆★	×	×
5	University of Toyama	◐	⌓	❐	×	☆	×	×
6	University of Tsukuba	◐	⌓	❐	×	☆★	×	×
7	Aichi University of the Arts and Music	●	⌓	❐	◎	☆★	×	n/a
8	Okayama Prefectural University	●	⌓	❐	×	☆	×	×
9	Sapporo City University	●	⌓	❐	×	☆★	×	×
10	Shizuoka University of Art and Culture	●	⌓	❐	×	☆	×	❍
11	Nagaoka Institute Of Design	●	⌓	❐	×	☆★	×	×
12	Kanazawa College of Art	●	⌓	❐	×	☆★	×	×
13	Chiba Institute of Technology	○	▲	❐	×	☆★	×	×
14	Tokyo Zokei University	○	⌓	❐	×	☆★	×	×
15	Aichi Sangyo University	○	⌓	❐	◎	☆	×	n/a
16	Osaka Sangyo University	○	▲	❐	×	☆	×	❍
17	Osaka Seikei University	○	⌓	❐	×	×	×	×
18	Kyoto Saga University of Arts	○	⌓	❐	×	☆	×	×
19	Tohoku Institute of Technology	○	⌓	❐	×	☆★	×	×
20	Nihon University College of Art Department of Design	○	▲	❐	×	☆★	×	×
21	Nagano University	○	⬡	❐	×	×	×	×
22	Kanazawa Gakuin University	○	⌓	❐	×	×	×	×
23	Kyushu Sangyo University	○	⌓	❐	◎	☆★	×	n/a
24	Kyushu Zokei Art College	○	⌓	❐	×	☆★	×	×
25	Kyoto Seika University	○	⌓	❐	×	☆	×	×
26	Kurashiki University of Science and the Arts	○	⌓	❐	◎	☆	×	n/a
27	Kobe Design University	○	⌓	❐	×	☆★	×	×
28	Sapporo Otani University	○	⌓	❐	×	×	×	×
29	Shibaura Institute of Technology	○	▲	❐	×	×	×	×
30	Seian University of Arts and Design	○	⌓	❐	×	×	×	×
31	Takushoku University	○	▲	❐	×	☆★	×	×
32	Tamagawa University	○	▲	❐	×	×	×	×
33	Tama Art University	○	⌓	❐	×	☆★	×	×
34	Tokai University	○	⌓	❐	×	☆	×	×
35	Tokyo University of Technology	○	⌓	❐	×	×	×	×
36	Tokyo Polytechnic University	○	⌓	❐	×	☆★	×	×
37	Tōhoku University of Art & Design	○	▲	❐	×	☆	×	×
38	Toyo University	○	⌓	❐	×	☆	×	×
39	Tokoha University	○	⌓	❐	×	×	×	×
40	Dohto University	○	⌓	❐	×	×	×	×
41	Nagoya University Of Arts	○	⌓	❐	×	☆	×	❍
42	Nagoya Zoukei University Of Arts & Design	○	⌓	❐	×	☆	×	×
43	Nishinippon Institute of Technology	○	⌓	❐	×	×	×	❍
44	Fukui University of Technology	○	▲	❐	◎	☆★	×	n/a
45	Bunka gakuen University	○	⌓	❐	×	☆	×	×
46	Hosei University	○	▲	❐	◎	☆★	×	n/a
47	Musashino University	○	▲	❐	×	☆	×	×
48	Musashino Art University	○	⌓	❐	×	☆★	×	×
49	Meisei University	○	▲	❐	×	×	×	❍
50	Yokohama College of Art and Design	○	⌓	❐	◎	×	×	n/a
51	Sojo University	○	⌓	❐	×	☆	×	×

◐ National ● Prefectural ○ Private ⌓ Art ·Design △ Engineering ❐ Product Design × None ◎ Integrated ☆ Master ★ Doctoral n/a (not apply)

to August 2016. Based on the data sourced, certain common items related to the integration of ecodesign and sustainability into product design courses were identified in both countries.

In order to reach a consensus of the items used in this research, the following terms are described:

Table 6.2 Japanese universities integrating sustainable design

	n/s	(%)
(a) General categories of universities		
National	6	11.8
Prefectural	6	11.8
Private	39	76.5
Total	51	100.0
(a1) General consideratios of sustainable design (SD)		
Integration of SD	8	15.7
Not Integrated of SD	43	84.3
Total	51	100.0
(a2) Universities categories (SD modules integration)		
National	1	12.5
Prefectural	1	12.5
Private	6	75.0
Total	8	100.0
(b) Design categories (SD modules integration)		
Art/craft/design	7	87.5
Engineering	1	12.5
Total	8	100.0
(c) Design degree (undergraduation)		
Product design (PD)	51	100.0
(d) Undergraduation integration of SD modules		
Integrated of SD modules	7	14.0
Not integrated SD modules	43	86.0
Total	50	100.0
(e) General postgraduate courses in product design (PD)		
Offer postgraduate courses	39	76.5
Does not offer postgraduate courses	12	23.5
Total	51	100.0
(f) Integration SD modules in postgraduation		
Integrated of SD modules	1	2.6
Not integrated of SD modules	38	97.4
Total	39	100.0
(g) Sustainability considerations on the present and future		
Not expressed sustainability considerations	38	74.5
Expressed sustainability considerations	5	9.8
No apply (n/a): universities that have integraded SD modules	8	15.7
Total	51	100.0

(a) Ecodesign and sustainable design or sustainability design approaches: the term ecodesign is defined as a strategic design management process that is concerned with minimizing full life cycle impacts of products and services [14]. Sustainable design (also called environmentally sustainable design, environmentally conscious design, etc.) is the philosophy of designing physical objects, the built environment, and services to comply with the principles of social, economic, and ecological sustainability [15]. A comparison of those two terms reveals that the approach of sustainable design is more wide and complex than ecodesign. However, the common point of both terms—environmental concern—is considered in this research.

(b) Product design course: the term product design covers a wide range of subjects, including theoretical and practical studies and research in general design, and also specialized subjects in design processes such as tools and methods for product and service development, for example, aesthetics, ergonomics, material selection, etc. Also in this research, the term product design involves the following common design fields: fashion design, textile design, packaging design, stationary design, furniture design, lighting design, equipment design, and service design as an element of product design.

(c) Module and seminar: the term module refers to the theoretical or practical class of design program. In general, there are 90 modules, with each lasting approximately 120 min, according to the education program of each university. In contrast, "seminar" refers to the activities of practical and theoretical researches on a specific theme.

(d) Undergraduate and postgraduate levels: the term "undergraduate" refers to bachelor's degrees with a specialization in the design field. Commonly, an undergraduate course is a comprehensive period of study that lasts between 3 and 4 years (or 6–8 semesters), depending on the education program of each university. In contrast, postgraduate study refers to the masters' or doctoral degree courses with a specialization in the design field. Generally, a postgraduate course is completed over a period of 2 years (or 4 semesters) for a master's course and 3 years (6 semesters) for a doctoral program [11–13].

6.6 Results

This section describes the results of the data collection process based on the method described in Sect. 6.4.

6.6.1 Overview of Japanese Product Design Course with Sustainability Considerations

In this research, 118 Japanese universities with design courses were identified, and 51 universities with product design courses were selected as case studies (Table 6.1).

During the collection of data from these 51 universities, the following items related to industrial design courses were identified: (a) categories of universities (national, prefectural, and private); (b) design categories (art/craft/design and engineering); (c) design degree (bachelor's degree in product design); (d) integration of ecodesign or sustainability modules at undergraduate level; (e) master's and doctoral degrees in product design; (f) integration of ecodesign or sustainable design modules at postgraduate level; and (g) universities that have not officially integrated sustainability or ecodesign in their curricula. However, the universities expressed the need for future integration of ecodesign or sustainable design in their design courses.

The data presented in Tables 6.1 and 6.2 show that of the 51 universities (item a), 11.8% are national universities, 11.8% are prefectural, and 76.5% are private universities. Table 6.2 shows that only eight universities (item a1) have integrated sustainability modules, six of which are private universities, one of which is prefectural, and one national (item a2). In items (b) and (c) of Table 6.1, 39 product design courses have art/craft/design approaches (76.5%), and 12 (23.5%) courses have engineering approaches. Of those 39 courses with art/craft/design, 7 universities (items b and d in Tables 6.1 and 6.2) have integrated sustainable design modules at the undergraduate level in their curriculum, while only 1 university with engineering approaches has integrated such a module (item f).

In item (e), 76.5% of universities (Tables 6.1 and 6.2) with product design courses have offered postgraduate programs, including master's and doctoral degrees with a specialization in product design. However, the extent of sustainable design modules at the postgraduate level remains very low (item f, 2.6%). In item (g) (Table 6.1), five universities (9.8%) have not implemented ecodesign or sustainability officially in their program, yet they have acknowledged the need to do so. They have expressed through their general introduction to the design courses the importance of such current issues: "Ecodesign and Universal Design" and "Earth-friendly and Human, Universal Design." They are concerned with universal design and activities that are intrinsically linked to social and environmental responsibility. For example, the private Yokohama College of Art and Design offers in the first semester of final (fourth) year of undergraduate study the following two themes, "universal design" and "sustainability," in Research of Product II [16]. These two themes are discussed in seminar activities and thus are not components of a formal module. The intention of these seminar activities is to provide students with the opportunity to learn sustainable design principles and prepare them, as future designers, to rethink the need and significance of sustainability.

Item (d) (Tables 6.1 and 6.2) presents the integration of ecodesign or sustainability module at undergraduate level. As an example, the private Kyushu Sangyo University has a module called "Universal and Ecological Design" for third year undergraduate students, which lasts 15 weeks [17]. Within this duration, 5 weeks are dedicated to the introduction of ecodesign, and 10 weeks are dedicated to universal design. Similarly, the private Fukui University also has a module focused on ecodesign with some introduction of universal design approaches. This 15-week module is called "Sustainable Design Theory" and is offered to third year undergraduates in 90-min lectures, with a total of 1350 h [18].

The private Kurashiki University's Department of Art and Design has a unique module called "Sustainable Design Theory" offered to second year undergraduates. The main focus of this module is to provide students with an opportunity to understand the characteristics of various materials (resin, metal, wood, paper, cloth, new materials, etc.) in order to develop a deeper understanding of the relationship between material, function, and form [19].

The national Chiba University is unique in that it has a postgraduate course that offers modules in ecodesign, called “Ecodesign Theory I and II.” According to international research on ecodesign [11], those two modules have been considered the best international examples in the ecodesign field. They are conducted in the first semester (both master’s and doctoral level), and each module lasts 90 min and takes place once a week [20]. The course is worth two credits and runs for a period of 16 weeks. The main contents of the modules are based on a doctoral dissertation entitled “The Role of Industrial Designers Toward Environmental Concern for Sustainable Product Development and Ecodesign” [21], which the current and future eco-products and services, strategies, and tools for product development with environmental concern are transmitted and discussed with the students. The students are also encouraged to participate in workshops and other relevant events related to sustainability and ecodesign that might be happening inside and outside the university. Annually, an increasing number of students express interest in ecodesign classes, which started with 96 postgraduate students from different engineering courses (e.g., horticulture, architecture, machinery, and urban planning). At the undergraduate level, a design course at Chiba University has not yet been established that integrates formally the sustainable development module, whereas no other national universities have integrated sustainable development modules formally into their postgraduate curriculum.

6.7 Discussion

According to experts [22], sustainability issues demand a systematic approach that uses skills, knowledge, and experience from many disciplines. The new environmental context means that industrial designers require new competencies in terms of ecodesign, sustainable innovation, and responsible design. Other experts [23–25] have also stressed that the current design education should be redirected to the development of ethical industrial designers and the integration of sustainability considerations into design curriculum is the key principle to achieving this objective.

In light of the arguments mentioned above, this section presents the main issues of the current integration of sustainability considerations in Japanese universities.

Unfortunately, the current number of Japanese universities that integrate sustainability considerations into their design curricula is relatively low. This result contradicts the initiatives of the Japanese Ministry of the Environment, which has stressed and encouraged the importance of integrating environmental education at all levels in order to achieve its goal of a sustainable society, as described in Sect. 6.2. Other points are that only one national university has officially integrated ecodesign modules in postdoctoral degrees and also that there is a lack of sustainable development modules at undergraduate level in national universities in general. Furthermore, there are no specialized courses in sustainable development in national, prefectural, and private universities.

In all national, prefectural, and private universities, there is a great contrast between the numbers of postgraduate programs offered by those universities in relation to the number of sustainable development modules offered.

The Japanese sustainable development modules at both undergraduate and postgraduate level are all single, short-term modules (e.g., one semester).

Based on the general results, the lack of an academic design program that focuses on sustainability in Japanese universities could indicate that such activities are a relatively new academic field in this context and also that there are limited experts in sustainability from an industrial design perspective. This fact is also related to previous studies [24–26] which indicate that the lack of staff training in and understanding of sustainability issues are main barriers to the official integration of sustainable development modules in design education programs.

6.8 Conclusion

In this research, Japanese universities with undergraduate courses in industrial design that have integrated ecodesign and sustainability into product design can be characterized with the following results. The number of ecodesign and sustainability modules that have been integrated formally at undergraduate and postgraduate level in Japanese universities is relatively low. The eight Japanese universities that offer industrial design courses with ecodesign and sustainability modules are characterized as optional modules with art/craft/design approaches, with the majority existing in private and prefectural universities. Only one national university has integrated ecodesign modules at postgraduate level.

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Chapter 7
Attributes of Carbon Labelling to Drive Consumer Purchase Intentions

Aila Khan and Yi-Chen Lan

7.1 Introduction

Although some forms of environmental labelling have been available for more than several decades, carbon labelling is a more recent development. Carbon labelling is ‘the practice of publicly communicating, via a label associated with a product or service, the greenhouse gas (GHG) emissions associated with the life cycle of that product or service’ ([1]; p. 348). The world’s first carbon label, i.e. the carbon reduction label, was published by Carbon Trust in the UK in 2006 [2]. Since then, a number of carbon-labelling schemes have been initiated worldwide. The objective of all these schemes is the same—to be able to provide reliable and meaningful information to consumers regarding the level of greenhouse gases emitted in the production of a product. Ultimately, it is hoped that such labels would help motivate consumers to choose products which have a smaller carbon footprint.

Reduction of carbon emissions is at the top of the environmental policy agenda [3]. This policy has significant impacts for two key stakeholders—businesses and customers. From the business perspective, carbon labelling can generate economic benefits [4]. When companies are able to communicate their sustainable practices to consumers [5], it positively impacts their image and reputation which may translate into greater sales. Some companies are also able to achieve cost savings by lowering their emission levels. There are two main kinds of carbon footprint which businesses deal with. First, there is the carbon footprint of a product. Depending on which method is used for calculations, carbon footprint may include all emissions related to the inputs, manufacturing, transportation, distribution, consumption and final disposal of the product. The second type is the carbon footprint of a manufacturing company which only includes the GHG emissions at the production stage of the product.

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An important stakeholder group for carbon-labelling initiatives is the end consumer. Businesses hope to influence consumers' buying behaviour. It is estimated that 72% of greenhouse gas emissions worldwide are related to household consumption [6]. Moreover, researchers claim that food production and consumption are responsible for 10–30% of an individual's total environmental impact [6]. In view of the massive impact of individuals and households on carbon emissions, there has been a marked increase in information and marketing campaigns promoting low-carbon lifestyle choices. Labelling on a product (i.e. logo, text and visuals) is seen as an important communication tool for businesses. While there is a legal requirement to disclose some information, marketers rely on labelling as the final promotional message before a purchase decision is made.

The aim of a carbon footprint label is to allow consumers to make informed decisions. If a label is better able to communicate the benefits of a product, consumers should be able to make the right choice. This should be beneficial for both consumers and businesses. However, research has shown that this is not always the case. In one study researchers found that the implementation of carbon labelling only resulted in a small change to consumer choices [7]. Similarly, some years back, a grocery chain, Tesco, decided to go back on its plans to introduce carbon labelling, claiming it was too expensive and time-consuming [8]. This demonstrates that if the costs of implementing carbon footprint labelling surpass the expected benefits, businesses will not adopt the initiative.

7.2 Carbon Footprint Labelling Implementation in Australia

The Australian Government has committed to reducing Australia's carbon emissions by 5% and 25% from 2000 levels by 2020. Australia initiated its Carbon Reduction Label scheme in 2009 [9]. It appeared on the market in 2010 [10] with a popular supermarket getting a range of its products certified. In Australia, Planet Ark—a specialised Australian association—took charge of assessing companies applying for the carbon label. The assessment was done using a measurement process of a subsidy company of the Carbon Trust in the UK. According to the process, once a product's carbon footprint has been calculated, the Trust's subsidy—Carbon Label Company—issues the certification [9]. Over the past 10 years, organisations such as the Carbon Reduction Institute, Country Carbon and Edge Environment have helped a variety of businesses (e.g. Dell, Fuji Xerox, Visy, Mercure Hotels and Health Insurance Fund) to tackle climate change and GHG emissions by launching a number of certification programmes.

In late 2010, the first grocery product range in one of the major supermarket groups in Australia was certified to use the carbon footprint label. However, the carbon footprint label initiative in Australia has only seen modest success as only a handful of organisations have adopted the carbon-labelling strategy [11]. Similarly, the rise in the ecological consciousness of consumers in other countries [12] has not always translated into purchase of environmentally friendly products [13]. According to one estimate, in spite of three-quarter Europeans showing willingness to purchase environmentally friendly products, only 17% reportedly bought such items which are identifiable through an environmental label [14].

Researchers have offered different reasons to explain this phenomenon. While one suggested reason is the time and financial cost involved [15], it is also quite possible that in many situations consumers are unable to identify environmentally friendly products from the rest. Such a process of identification becomes even more difficult with many grocery products being sold as commodities without the use of relevant branding or labelling. With the presentation of our conceptual model, we hope to propose how consumers' purchase intentions towards carbon-labelled products can be impacted by assuring an effective labelling scheme.

7.3 Communication of Carbon Footprint Labelling

In today's competitive world, consumers are exposed to approximately 4000–10,000 ads per day [16]. In such a cluttered marketing environment, product labelling becomes an important communication tool. Marketers are diverting a growing proportion of their promotional budget to nontraditional methods for communicating with customers [17]. Moreover, it is now recognised that much of the consumers' decision-making happens in the store aisles [18]. Labels provide a wide range of information to help consumers make choices [19] and can play a critical role on a last 5-s advertisement before the consumer makes a purchase decision.

Traditionally, a key objective of food labels was to ensure consumers are able to make healthy and safe product choices. However, in view of the values held by a 'conscious consumer', it is argued that such a person would make a choice which would be beneficial not just for the individual but also for the society at large. As part of their core values, conscious consumers are concerned about the world and want to play a role in making it a better place [20].

It can be argued that a labelling-focused communication programme can bring about a stepwise process of attitude change. Applying McGuire's [21] communication output model, we anticipate the following pathway to the development of positive attitudes towards a carbon-labelled product: an individual (a) gets exposed to information about the carbon emissions of a product (e.g. through a label displayed on the product), (b) attends to the product information being communicated via the label, (c) processes the information about the product and therefore (d) develops a positive attitude towards the product along with its relevant attribute.

7.4 Cue Utilisation Theory and Research Model

Consumers look for various cues to evaluate a product before purchasing it. According to cue utilisation theory [22], consumers evaluate a product by looking at intrinsic and extrinsic cues. Intrinsic cues refer to physical attributes of a product such as the colour, size, shape and succulence of the produce [23]. Extrinsic cues, on the other hand, are not part of the physical product. These include cues such as price, package and label. However, these attributes are still important in the overall evaluation of the product. These features also include the use of environmentally friendly production methods [24] or a product's carbon footprint. Some of these cues are more salient than the others. While previous research has shown that consumers examine the quality of grocery items through visual inspection, and the use of touch and smell, it is nearly impossible for consumers to verify the extent of carbon footprint on unlabelled products.

In this conceptual paper, we propose that a product's carbon footprint is a credence-based attribute [25] as it is difficult for consumers to evaluate the performance of the product on this particular dimension. A carbon label, highlighting a product's carbon footprint, may be seen as an extrinsic cue which could help consumers with the final purchase decision.

Understanding consumers' evaluation of carbon labels is important for two reasons: first, previous research has shown that while quality, taste, nutrition and price are considered to be important attributes during grocery purchases, a product's carbon footprint is not an attribute which features highly on consumers' list of relevant food attributes [26]. Awareness and concern about the environmental impact of products has been a challenge, especially with the purchase of grocery items; second, consumers' perceptions regarding the accuracy and credibility of the information communicated via a carbon label are poorly researched [27]. With numerous 'climate-friendly' claims being made by marketers, consumers need information that is reliable and trustworthy [28]. Moreover, earlier research studies reported that EU consumers found environmental information on product labels as difficult to understand [29].

Product-related information is disseminated through a number of channels including the product's label. Previous studies have indicated that information presented on a label is assessed by consumers [30]. In line with the universal norms of pragmatics presented by Habermas [31], it has been recognised that these norms provide a benchmark for successful communication [32, 33].

Consumers expect credible information to be provided to them (i.e. the fulfilment of the norm of truthfulness). If a consumer perceives the information on a product's label to be accurate consistently, the consumer begins to trust the manufacturer which may result in the development of positive attitudes towards the product. However, if the information is perceived to be incorrect, then the communication process breaks down. This may in turn impact the type of attitudes consumers hold towards the product (Fig. 7.1).

Similarly, in line with the norm of sincerity [31], it is important for a carbon label to be perceived as reflecting the company's sincere and virtuous efforts at being environmentally conscious. It is not surprising to find consumers overwhelmed by the plethora of corporate-sponsored socially responsible claims. It has been argued that consumers find it difficult to distinguish between truly virtuous firms and those engaging in mere rhetoric to take opportunistic advantage of the current trend of environmental consciousness [34]. If consumers perceive carbon labelling to be an

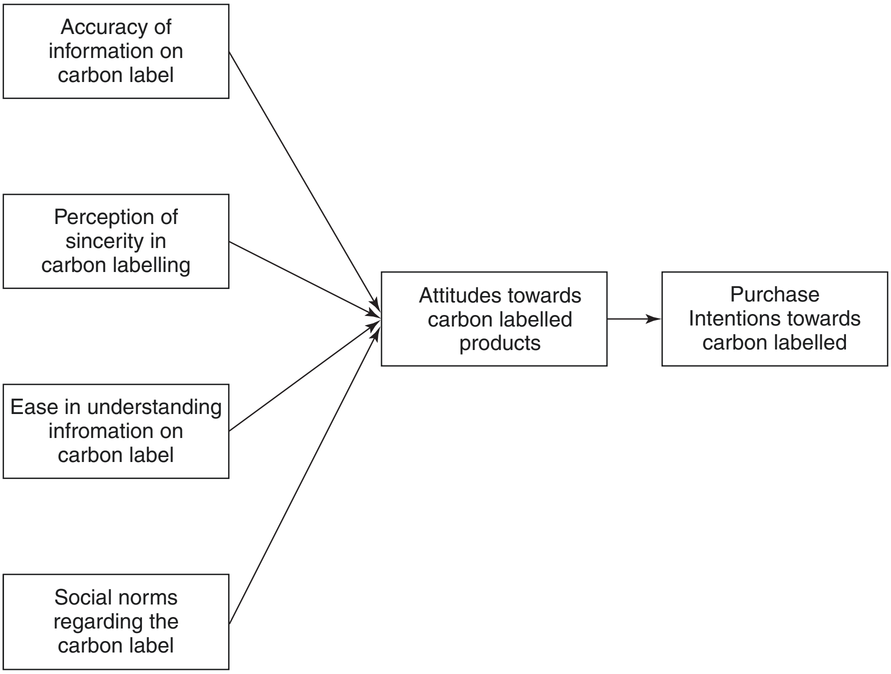

Fig. 7.1 Research model: impact of carbon-labelling attributes on consumer attitudes and purchase intentions

attempt at 'greenwashing' [35], it may negatively impact attitudes towards the product. On the other hand, if consumers believe that the company is genuinely making an effort at environmental consciousness, then attitudes towards the carbon-labelled product would also be positive.

The norm of comprehensibility [31] is based on the notion that information presented on a carbon label must be understandable. A number of studies (e.g. [36])—especially in the nutrition domain—have looked at the importance of ease in understanding and interpreting the information on a product's label. It has been reported [37] that a proportion of consumers find environmental labels difficult to understand. This could be due to the technical language used or the way the information has been presented. If a consumer is easily able to comprehend the level of carbon footprint of the product, consequentially it would impact the consumer's attitudes towards the carbon-labelled product as well.

Finally, the extent to which an organisation's carbon labelling is able to earn legitimacy in the eyes of its stakeholders (i.e. the norm of legitimacy) is an important factor in the success of the overall communication process [38]. Legitimacy is defined as a 'generalised perception or assumption that the actions of an entity are desirable, proper or appropriate within some socially constructed system of norms, values, beliefs and definitions' [39]. A corporation that aligns with social norms—or tries to promote a new set of social norms—is likely to be viewed as trustworthy, gains popular support and is less likely to be susceptible to undeserved scepticism and attack [39]. If a product's carbon label is positively evaluated by a third party, such as the media [40], a certifying agency (e.g. the Carbon Reduction Institute) or an award-giving entity, then the carbon-labelling initiative gains legitimacy in the eyes of the public. On the other hand, without demonstrating the positive assessment by important stakeholders, it is quite possible that the label on its own is seen as an attempt at self-promotion. Therefore, we propose four hypotheses:

H1 Consumers' perceptions of accuracy of information on carbon label will be linked to their positive attitudes towards the carbon-labelled products.

H2 Consumers' perceptions of sincerity of a product's carbon label will be related to their positive attitudes towards the carbon-labelled products.

H3 Easy in understanding a carbon label will lead to positive attitudes towards the carbon-labelled products.

H4 Certification of a carbon label by an authorised agency will be linked to positive attitudes towards the carbon-labelled products.

The attitude-intention link is well-recognised as per the theory of reasoned action [41]. Attitude represents a person's general feeling of favourableness or unfavourableness towards a particular behaviour. If a person evaluates a carbon label more favourably, then the individual would also be more likely to form favourable intentions towards purchasing the product. Alternatively, if a label results in an overall unfavourable evaluation, then the person's behavioural intentions would also be negatively impacted.

Therefore, it can be proposed that:

H5 Attitudes towards carbon-labelled product will be positively associated with purchase intentions towards the products.

7.5 Discussion and Conclusion

A number of policy interventions have failed to make a significant impact on the sales of low-carbon products. It is argued that in an environment cluttered with marketing messages, it is important to offer simple yet accurate—and trustworthy—information to consumers. This conceptual paper presents a model that maps out the proposed impact of a carbon label on consumers' buying decision.

In spite of all the advances in marketing communications, the issues with labelling content have been a constant debate [42]. Many health organisations [43] regularly deal with consumer concerns with labelling. In spite of the new labelling schemes initiated by the Australian Government, consumers still get confused with technical and ambiguous information [44].

It is envisaged that the empirical data gathered from consumers through the proposed research model will help in better understanding (a) the link from the norms of communicative action to positive attitudes towards the product and (b) the association between the attitudes towards carbon-labelled products and the purchase intentions towards the products. Each individual norms of communicative action may be assessed in the future to draw the priority for fine-tuning the company's marketing strategy and focus.

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Chapter 8
Development of a Municipal Waste Management System from Environmental and Economic Evaluation Perspectives: A Best Available System Methodology

Hao Hu, Ruixi Zhao, Kenta Omura, and Hiroshi Onoda

8.1 Introduction

Concern over waste management problems has heightened lately owing to the escalation of environmental issues. Meanwhile, the diversity of waste continues to increase due to the expansion of economic and social activities and associated lifestyle changes. Simultaneously, it is a trend that municipal solid waste (MSW) systems are becoming more diverse and better-equipped due to pressures owing to maintaining pressures from final disposal site, reducing dioxin, and conducting 3Rs (Reduce, Reuse, Recycle) policies [1].

Under these circumstances, and with the intention of encouraging the development of a recycling society, revising the MSW system is an urgent task from both environmental load and economic evaluation perspectives [2]. Recently, there are various Life Cycle Assessment (LCA) researches in the MSW system field. For instance, Tabata et al. [3] investigated the LCA efficiency based on statistical data of incineration facilities. And, they also offered integrated environmental influence evaluation of waste treatment scenario through DTT (Distance-to-Target) method [4]. Furthermore, Nakatani et al. [5] conducted integrated assessment based on cost-benefit analysis [6]. Meanwhile, Amano et al. studied on LCA evaluation of MWS system from GHG emissions and landfill disposal perspective. Besides, Matsuto et al. [7] developed a practical calculation program H-IWM, an Excel version, for simulating municipal waste treatment planning from treatment amount, cost, and energy consumption view. Other researchers analyzed waste energy recycling

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society using LCA and discussed the advantages and disadvantages of waste management regional expansion.

However, in the previous studies, both economic and environmental simulations with multiple cases (e.g., incineration, gasification melting, power generator, ash melting, fly ash recycle, crushing process) are hardly found, because plant makers' LCI databases are insufficient and literatures are mainly focusing on a single incineration plant, and it is seemingly found to be competent categories of technologies. In this research, we develop a LCI database through collecting data from 14 representative plant makers that occupy most market share in Japan and investigate on their intermediate process plants (e.g., incinerator, power generator melting, fly ash recycle).

Meanwhile, we develop a more accurate management system targeting MSW system through applying this database. In details, MSW management system, namely, Best Available System (BAS) methodology, is developed based on LCA (Life Cycle Assessment) and LCC (Life Cycle Cost) analysis. This BAS methodology aims to improve and sophisticate the MSW recycling system and provides quantitative indicators for evaluations from both environmental load and economic evaluation perspectives.

In the LCA analysis, we apply ELP (environmental load point), an index previously developed by the authors, which solves the single index issues of previous studies. And different with other integrated method, ELP reflects the changes of human environmental awareness with changes of time.

8.2 Concept of BAS Methodology

It has been necessary for municipalities to conduct quantitative environmental load evaluations and cost estimation when establishing waste treatment practices. Hence, the BAS methodology focuses on MSW agencies and provides analysis from their perspective by applying LCA and LCC. Meanwhile, it evaluates waste treatments (including collection and recycling, midterm treatment, transport, final disposal, and use) and the recycling system.

The environmental load evaluation is calculated using Technology Life Cycle Assessment (TLCA), which applies for technology and evaluates treatment and recycle based on LCA method. The TLCA is a quantitative assessment of input and output to the environmental load carried by humans and ecosystems. For instance, the assessment involves quantifying not only the recycling and waste management done by the plant but accounts for environmentally important metrics of the plant's actual equipment as well. The BAS has the following advantages:

1. It evaluates a series of MSW processes that range from collection and recycling to final use and disposal treatments.

2. The environmental load evaluation database of incineration and melting (e.g., input and output amounts at different treatment scales, power generation efficiency) is compiled based on the plant maker's design and estimated value.
3. It enables calculation of indices for recycling rate, energy expended in the recycling process, and final disposal treatment for different evaluation scenarios.
4. The BAS methodology makes it possible to develop the ELP (environmental load point), introduced by the authors in a previous study, into a more comprehensive system [8].

8.3 Outline of ELP Integrated Index

In the LCA field, expressing the impact category within a single index is called integrated evaluation [9]. The authors developed this integrated evaluation method based on the Panel Method in the previous study. The Panel Method suggests environmental improvement priorities and provides a comparison of the suitability of different decisions. The ELP is developed by setting up nine impact categories (e.g., energy depletion and climate change) and making weight values for each category by applying the survey results [10].

As shown in Table 8.1, there are nine impact categories, and analysis of their characteristics is conducted in each by applying weight coefficients, sorted by importance of CO_2, NO_x, BOD, heavy metal, and so on. This allows us to estimate the index of each category and thereby conclude the degree of importance of each. The ELP integrated index is calculated by multiplying the outcome of the characteristic analysis with the degree of importance [11]. The formula is shown in Fig. 8.1.

In this method, assessing product pairs with different functional units such as automobiles and PET bottles becomes efficient.

Table 8.1 ELP impact category [12]

Impact category	Weighting coefficient	Target items
Energy exhaust	Low heating value/exploitable year (crude oil = 1)	5
Climate change	GWP100 × 1 (CO_2 = 1)	38
Ozon depletion	GDP (CFC-11) = 1 × 2	24
Air contamination	AP (Acid potential) (SO_x = 1)	7
Resource contamination	1/exploitable year (iron ore)	32
Air pollution	1/Environmental standard (SO_x = 1)	10
Ocean and water contamination	1/Environmental standard (BOD = 1)	37
Waste treatment issue	1 (weight conversion)	1
Ecosystem influence	ECA (ecotoxicological classification factor) (Cr = 1)	32

[ELP]

$$A_j = \sum_k (C_{j,k} \times TQ_k)$$

$$ELF_k = \sum_j (C_{j,k} \times W_j / A_j) \times 10^{16}$$

$$ELP_i = \sum_k (ELF_k \times Q_{i,k})$$

ELP: integrated index of product *i* (matter)

A_j: Total annual load of category *j*

$C_{j,k}$: Weight coefficient of project *K* in category *j*

TQ_k: Annual Input and output (kg) *

W_j: Important degree of category *j*

ELF_k: Integrated index of project *K* (ELP/kg)

$Q_{i,k}$: Input and output of project *K* for product *i* or other

_i_: Product or matter
_j_: impact category
_k_: environmental project

*** Annual input and output is set based on Japanese and global value**

Fig. 8.1 ELP integrated index formula [12]

8.4 Methodology of BAS

8.4.1 Evaluation Flow

The BAS methodology integrates waste components and classifies collections based on the current state of the evaluation system. And it contains the collection, midterm treatment, and final disposal (recycle); see Fig. 8.2.

Meanwhile, the BAS methodology creates databases so as to categorize MSW systems. It also sets default values based on common designs and anticipated value from Japanese plant makers in case measured data is insufficient when evaluating the environmental load data (input and output). BAS methodology provides an evaluation outcome including cost, ELP integrated index, and specific index (e.g., GHG emissions, landfill reduction amount, energy consumption, SO_x, and NO_x). Besides, it offers comparable analysis among various cases through case studies. Furthermore, the BAS proposes recommendations for MSW system improvement and judgment of new system introduction based on users' financial situation and purposes.

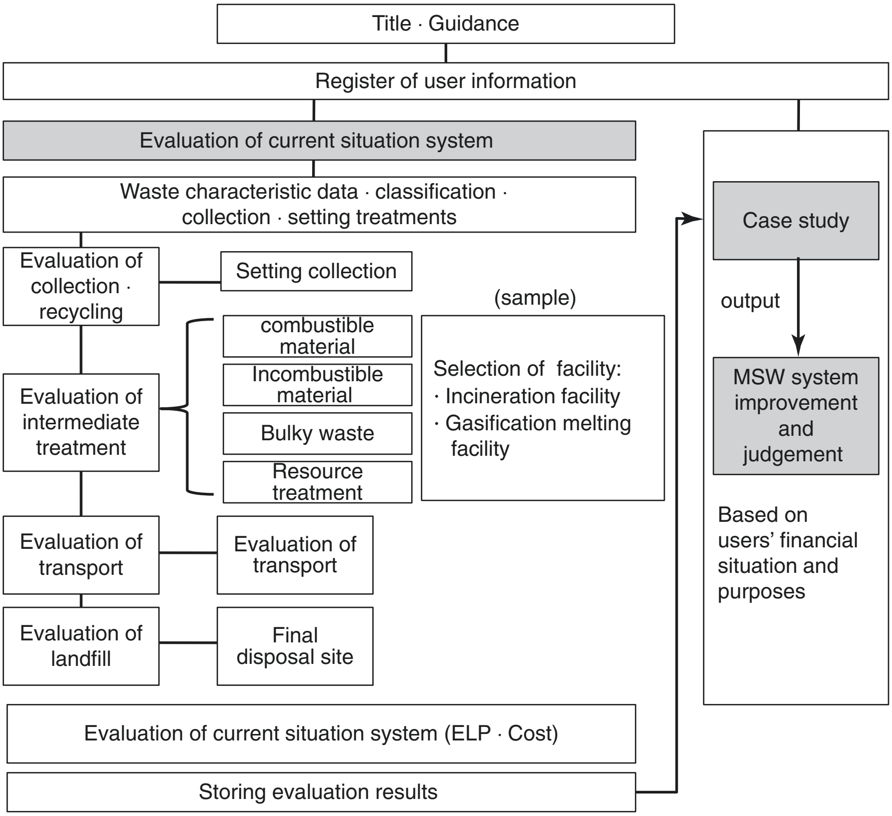

Fig. 8.2 Evaluation flow of BAS

8.4.2 *Waste Components and Chemical Elements Setting*

After setting the types and components of waste and inputting data of a target city, the BAS methodology enables us to calculate the amount of air supply for combustion, gas emission from combustion, heating value, and power generation from incineration treatment. In this method, heating value means low calorific value, which is the same as regular heat load calculation. Measuring data or using a similar value is required when applying the Steuer formula (8.1 for calculating combustibles' high heating value based on chemical element analysis [13]. Meanwhile, the low heating value is calculated using the following formula (8.2):

$$\mathrm{Hh} = 339.4\left(c - 3 \times \frac{o}{8}\right) + 238.8 \times 3 \times \frac{o}{8} + 1445.6\left(h - \frac{o}{16}\right) + 104.8s \ \left(\mathrm{kJ/kg}\right) \qquad (8.1)$$

$$\mathrm{Hl} = \mathrm{Hh} - 25(9h + W) \tag{8.2}$$

Hh: Waste high heating value (kJ/kg)
Hl: Waste low heating value (kJ/kg)
h: Hydrogen content in Wetness waste (%)
W: Moisture content in Wetness waste (%)
o, h, c, s: Weight in combustible material (%)

The BAS develops a database of waste in 59 categories to cope with classifications in different municipalities. Hence, it is able to evaluate and set detailed waste components. For those municipalities whose data is insufficient, this study develops a default value database (Table 8.2) [6].

8.4.3 Building LCA Databases

Midterm and final disposal treatments (recycled) are shown in Fig. 8.3. The input, output, and cost are added, and environmental load is calculated using the ELP methodology. Contrasting with the ELP method, this research enables us to illustrate individual indices such as CO_2 emissions, primary energy consumption, final disposal amounts, etc.

This research participated in Osaka Science & Technology Center waste treatment technology LCA workshop, which compiles LCA and LCC databases based on MSW information collected from member companies. This research covers almost all plant categories through applying data (facility design and plan values) collected from 14 major Japanese MSW treatment plant designers. Nowadays in Japan, the number of waste incineration treatment facility has reached a peak, and there is a decreasing trend currently. Constructions of incineration facilities in large scale have started after conducting wide-area waste treatment plan (dioxins control countermeasures, 1997). In this study, we select incineration facility data between 2000 and 2006 considering the machines' working life. The evaluable technologies and building characteristics used in the BAS methodology are shown in Table 8.3.

As an example of a common MSW treatment, incineration technology's database building and default value setting will be described in detail.

8.4.3.1 Building a Database of Incineration Treatment and Setting Default Values

We have collected LCA data (1997–2006) from plant designers about incineration treatment, stoker-type incineration, ash melting, and gasification melting. The default values of incineration treatment are created based on the average values of these

Table 8.2 Database of waste component default values (excerpt)

		Three components			Chemical elements in combustibles					
		Combustibles (%)	Moisture (%)	Ash (%)	C (%)	H (%)	O (%)	N (%)	Combustibility (S%)	Volatility (Cl%)
Paper										
	Paper pack for beverage	78	20	2	44	6	49	0.2	0.02	0.4
	Carton box	78	20	2	44	6	49	0.2	0.02	0.4
	Other paper package container	75	20	5	44	6	49	0.2	0.02	0.4
	Other paper exclude package container wastes	70	20	10	44	6	49	0.2	0.02	0.4
Kitchen refuse (garbage)		18	78	4	42	6	34	3	0.1	0.3
Fibers		79	20	1	42	6	42	0.5	0.04	0.2
Plants (Grass and Woods)		52	45	3	46	6	40	0.9	0.02	0.2
Other combustibles		33	57	10	44	6	49	0.2	0.02	0.4
Plastic										
	PET	74	26	0	62	4	34	0	0.01	0
	Other plastic-made package container	71	26	3	74	11	11	0.2	0.02	3.9
	Other plastic waste exclude package container	71	26	3	74	11	11	0.2	0.02	3.9
Rubber and leather		72	14	14	66	8	18	1.1	0.33	4.7
Iron										
	Steel cans	0	5	95	0	0	0	0	0	0
	Other iron waste exclude package containers	0	5	95	0	0	0	0	0	0

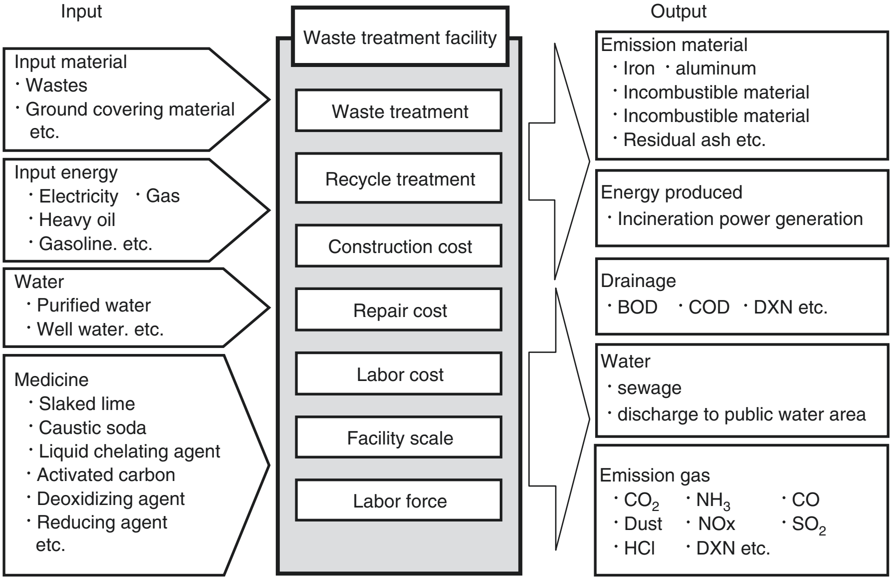

Fig. 8.3 Midterm and final disposal input and output

Table 8.3 Database of BAS methodology

Applicable treatment methods	Calculation of measured value	Default value DB
Simple incineration	○	○
Incineration power generation	○	○
Gasification melting	○	○
Ash melting	○	○
Washing ash	○	○
Fly ash recycle	○	○
Eco cement treatment	○	○
Crushing treatment	○	○
Waste paper	○	○
Cans	○	×
PET	○	○
Bottle	○	×
Waste cloth	○	×
Carbonization	○	×
Methane fermentation	○	×
Composting treatment	○	×
Ethanol treatment	○	×
BDF treatment	○	×
Waste plastic liquefying treatment	○	×
Waste plastic blast furnace fuel treatment	○	×
Dry battery	○	×
Fluorescence tube	○	×
Final disposal treatment	○	×

processes. Regarding the default values of stoker incineration and gasification melting, we assume waste input is 600 t/day and the heating value is 2400 kcal/kg. Meanwhile, the plant electricity consumption and fuel subsidy are decided by the waste input per ton. Emission gas treatment medicine and relative input amounts are decided by the type of treatments. Furthermore, the calculation of ash melting follows the ratio that the incineration's main ash is composed of 90% total ash, while incineration ash accounts for 10%. Details of incineration LCI defaults are shown in Table 8.4.

Table 8.4 Incineration LCI default

Items			Unit	Incineration amount	Melting burned ash (main ash) + fly ash	Gasification melting
				2006	2006	2006
				Average of 5 companies	Average of 5 companies	Average of 5 companies
Input	Waste input		kg/day	6.00E+05	1.04E+05	6.00E+05
	Power consumption amount		kWh/day	7.23E+04	1.04E+05	1.10E+05
	Fuel (auxiliary)	Kerosine	kg/day	0.00E+00	1.06E+03	4.53E+02
		Coke	kg/day	0.00E+00	0.00E+00	6.00E+03
	Exhaust gas	Slaked lime	kg/day	9.64E+03	3.54E+02	6.00E+03
	Treatment	Active carbon	kg/day	2.81E+02	1.36E+01	2.69E+02
	Chemical	Ammonia	kg/day	1.18E+03	–	9.86E+02
		Urea	kg/day	0.00E+00	–	1.85E+03
		Caustic soda	kg/day	0.00E+00	–	0.00E+00
Output	Gas emission	CO_2	kg/day	6.27E+05	1.05E+04	6.44E+05
		NO_x	kg/day	2.37E+02	5.00E+00	3.27E+02
		SO_x	kg/day	2.64E+02	3.00E+00	2.77E+02
		HCl	kg/day	1.67E+02	3.00E+00	1.94E+02
		DXNs	kg/day	5.06E−05	5.65E−09	4.96E−05
		Dust	kg/day	4.84E+01	1.00E+00	5.03E+01
	Byproducts	Metal	kg/day	0.00E+00	3.15E+03	8.52E+03
		Slag	kg/day	0.00E+00	7.96E+04	6.81E+04
	Residue	Incineration ash	kg/day	8.91E+04	–	–
		Incineration fly ash	kg/day	2.56E+04	–	–
		Incineration unfit matter	kg/day	0.00E+00	–	–
		Melting fly ash	kg/day	0.00E+00	7.25E+03	1.89E+04
		Melting unfit matter	kg/day	0.00E+00	8.20E+03	1.02E+04
	Power generation		kWh/day	3.45E+05	–	3.27E+05

8.4.3.2 Building Database of Incineration Power Generation and Setting Default Values

To assess the power generation of incinerated waste, the survey “analysis of waste incineration facilities’ power generation efficiency” is conducted among plant designers. The LCI database is created based on this survey and the incineration power generation value. Efficiency is analyzed via relationships among treatment scale, steam conditions, and input heating values. For the 12 cases in Table 8.5, we conducted a survey about waste power generation. The outcome of the survey is presented in the database (excerpt) and shown in Table 8.6.

Based on the above survey, we analyzed the influence of treatment scale, steam conditions, and input heating values of waste power generation efficiency. Regarding treatment scale, efficiency will increase by 3% if the facility is 600 t/day, and by 4%

Table 8.5 Twelve case studies

Case	Scale of the facilities	Steam conditions	Input waste
1	100 t/day	300 °C × 30 ata	1600, 2000, 2400 kcal/kg
2		400 °C × 40 ata	
3		450 °C × 60 ata	
4		500 °C × 100 ata	
5	300 t/day	300 °C × 30 ata	
6		400 °C × 40 ata	
7		450 °C × 60 ata	
8		500 °C × 100 ata	
9	600 t/day	300 °C × 30 ata	
10		400 °C × 40 ata	
11		450 °C × 60 ata	
12		500 °C × 100 ata	

Table 8.6 Incineration power generation database (extract)

Eight targeted companies	Unit	2003 database in average			
Waste treatment amount	t/day	600			
Heating value of input waste	kcal/kg	2400			
Steam condition	°C	300	400	450	500
	ata	30	40	60	100
Purchasing power amount	kWh/day	0	0	0	0
Heating value of input waste	kWh/day	1.7E+06	1.7E+06	1.7E+06	1.7E+06
Heating value of input fuel	kWh/day	5.8E+04	5.8E+04	7.6E+04	8.9E+04
Total heat input	kWh/day	1.7E+06	1.7E+06	1.8E+06	1.8E+06
Power generation amount	kWh/day	2.9E+05	3.3E+05	3.6E+05	4.0E+05
Power generation efficiency	%	1.6E+01	1.9E+01	2.1E+01	2.2E+01
Plant consumption	kWh/day	1.1E+05	1.1E+05	1.1E+05	1.1E+05
Selling power amount	kWh/day	1.7E+05	2.1E+05	2.5E+05	2.8E+05
Power transmission efficiency	%	9.8E+00	1.2E+01	1.4E+01	1.6E+01

if. Regarding the steam conditions, it was found that the efficiency will be significantly improved under high temperature and high pressure. For instance, the efficiency will be 10–15% if under 300 °C × 30 ata and 14–21% if under 500 × 100 ata. The survey outcome also shows that the efficiency will drop sharply when the treatment scale is reduced.

The BAS methodology enables the calculation of the proportion interpolating according to the treatment scale and heating value of input waste.

8.4.3.3 Building Database of Emission Gas Treatment and Setting Default Value

A suitable emitted gas treatment is necessary because the gas emitted accounts for more than 50% of the environmental load during MSW's incineration process. Utility and cost databases were created based on a survey called "Emitted gas treatment and cost efficiency" about NO$_x$, SO$_x$, HCl, and DXN treatments. The investigated treatment is illustrated in Table 8.7. As a sample, the outcome of NO$_x$ treatment (extract) is shown in Table 8.8.

Table 8.7 Target gas and treatment technology

Target gas for treatment	NO$_x$	SO$_x$	HCl	DXNs
Treatment technology	• Urea blowing method • Denitration catalyst method	• Slaked lime blowing method • Wet smoke gas cleaning method • Na series of medical blowing method		• Catalytic reaction tower • Activated carbon blowing method • Activated carbon absorption method • Catalytic reaction tower + Activated carbon blowing method

Table 8.8 Gas treatment database (extract)

Item		Unit	Seven companies in average
Treatment targe	NO$_x$	–	–
Treatment technology	Urea blowing method	–	–
No$_x$ emission concentration	Concentration before treatment	ppm	1.4E+02
Medicine input	Reduced concentration	ppm	7.7E+01
	Urea	kg/year	8.8E+05
Cost	Waste among/t	kg/t	4.8E+00
	Construction cost	Yen	3.6E+07
	Repart cost	Yen/year	1.7E+06
	Urea	Yen/year	1.6E+07

This study found that facility fees and initial cost of denitration catalyst and wet smoke gas cleaning methods increase sharply compared with urea blowing and slaked lime blowing methods. Regarding running cost, NO_x and HCl increase 3–4 times.

8.5 Application of BAS Methodology in Municipalities

8.5.1 Evaluation Background

We conducted a case study and applied BAS methodology in municipality city A. The waste (excluding resource waste) treatments are conducted by an incineration power generation facility and a crushing facility. The incineration ash emitted from the incineration facility and incombustible residue from the crushing treatment facility were treated by landfilling in a final disposal site outside the city. In this research, we assess the current situation of the waste treatment system in city A and provide improvement proposals, which range from evaluating its collection (recycling) to its final disposal (use). In cases where data is insufficient to perform analyses, we apply BAS's default values.

8.5.2 Evaluation of Current Treatment

Table 8.9 summarizes the incineration facilities in city A. Figure 8.4 shows the calculation outcome of ELP based on the current treatment cost of different processes. It illustrates that the incineration power generation process is the process most expected to go down in cost as it has the highest cost and largest ELP. We recommend improving the level of detail in the classification of kitchen garbage. Besides, the final disposal treatment (landfill) of incineration ash also has a high cost and ELP. Hence, we suggest that city A introduce and apply melting technology to reduce the amount of incineration ash produced.

Table 8.9 Incineration facilities in city A

Operation year	1994
Processing capacity (t/day)	600
Treatment system	Stoker
Operation pattern	Continuous operation
Generation power (kW)	7000
Smoke control equipment	Electric precipitation
Annual throughput (t/year)	135,936
Operation rate	0.68

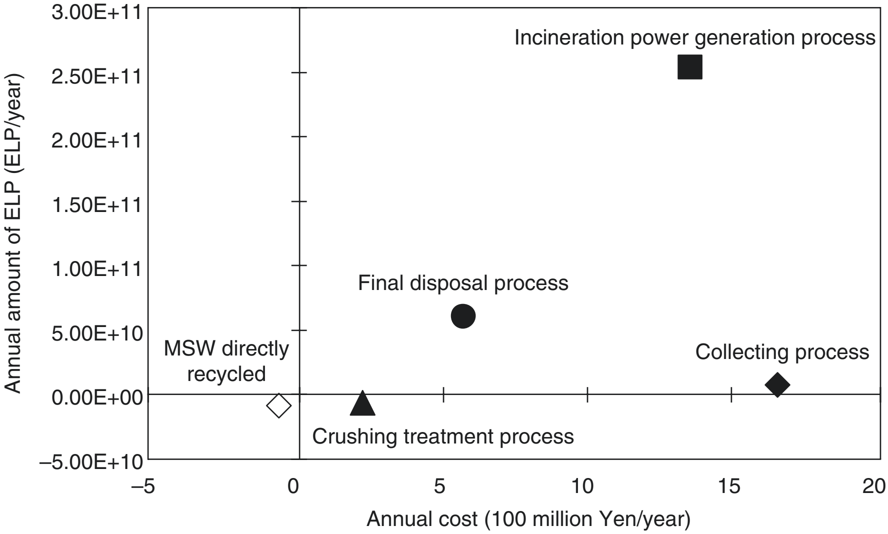

Fig. 8.4 ELP and cost in different processes

8.5.3 *Case Study*

The hypothetical scenarios in each case and their parameters are shown in Fig. 8.5. Through applying the BAS methodology, the ELP and cost database of input and output amounts for treatment processes are able to inform a variety of improvement scenarios. In this study, using kitchen garbage as an example waste type, we attempt to create a scenario following an incineration ash reduction policy, which is based on incineration output reduction perspectives and involves introduction of melting technology. Regarding the cost, we calculate it based on treatment expense (see Table 8.10). And about ELP, we calculate it based on BAS methodology databases.

The cost and ELP outcomes of each case are shown in Fig. 8.6. About the cost, it becomes larger than current situation (case 1) in cases 2–6 due to the introduction of ash melting and change of gasification melting. And about the fly ash recycle, it is found that there is almost no expense variation due to the little recycle amount. And, we also found that the cost is larger in case 6 than that of case 1, which is because the expense increases with recycling and bio-gasification treatment. However, the ELP in case 6 decreases significantly, which is smaller than that in cases 2–5 due to the decrease of final disposal, ash technology, and incineration amount. Hence, case 6 is the most effective one for ELP reduction if conducting bio-gasification, but the cost also increases relatively.

The ELP relative reduction effectiveness that represents ELP mitigation amount in step with increasing each cost unit is illustrated in Table 8.11. And we found out that ELP reduction effectiveness of CASE 5 is the highest.

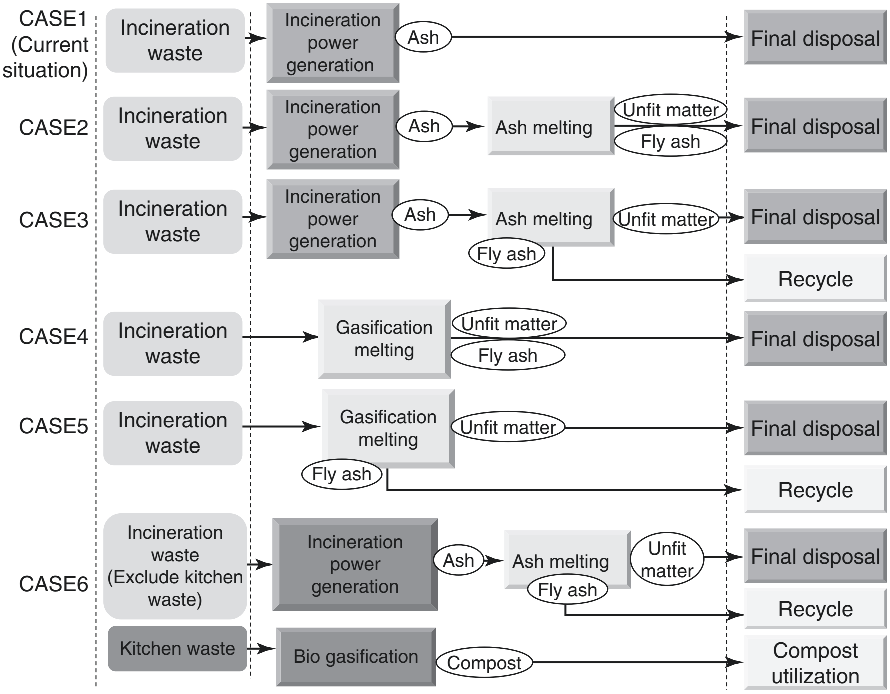

Fig. 8.5 Hypothetical scenarios in each case

BAS is an integrated evaluation method that analyzes the cost and ELP, and it also provides assessment value of material recycling, energy recycling, CO_2 emission, and final disposal amount. And comparisons among cases are shown in Table 8.12.

The material recycling is the process that collects iron, metal, and melting slag that come from facilities like crush treatment and direct recycling. Moreover, a trend of relation is also found from the outcome. In cases 2–6, the results demonstrate that the final disposal amounts decrease while the CO_2 emissions increase. And the scenario varied according to the preference for policies between landfill and CO_2 reduction. In this study, we are able to analyze and assess the trade-off factors by applying the BAS based on ELP, and it is proofed that the ELPs of cases 2–6 are more effective and integrated than the current situation (case 1).

However, the cost has to be increased in each scenario. Hence, it is necessary to conduct deep consideration of each system based on the municipal financial situations. And, corporations among neighboring municipalities are recommended so as to enlarge the scale merit and reduce the economic burden.

8.6 Summary

The development of evaluation tools for MSD treatment systems' ELP and cost and verification of their applicability is summarized in the following points:

Table 8.10 Calculation of treatment cost[a]

Items	Incineration power generation	Ash melting	Gasification melting	Incineration power generation (exclude kitchen waste)	Fly ash recycle	Final disposal	Kitchen waste bio-gasification
Treatment amount t/year	135,936	10,091	135,936	97,154	–	–	–
Construction fee[b] 1000 yen/year	1,000,000	171,008	1,026,353	588,235	–	–	–
Labor cost[c] 1000 yen/year	140,000	105,000	210,000	140,000	–	–	–
Utility cost 1000 yen/year	123,665	132,536	183,918	84,315	–	–	–
Maintenance cost[d] 1000 yen/year	600,000	102,605	615,812	600,000	–	–	–
Power selling income 1000 yen/year	−504,898	0	−394,674	−549,209	–	–	–
Total 1000 yen/year	1,358,766	511,148	1,641,409	863,340	–	–	–
Treatment/consign unit 1000 yen/t	10.0	50.6	12.1	8.89	50.0	27.9	35.0

[a] Hearing survey from whom it concerned

[b] The construction fee is calculated considering lifespan of 20 year

[c] The number of workers are set as: 20 people for incineration generation,15 people for ash melting, 30 people for gasification melting

[d] Calculation by using 3% construction fee

1. We developed a Best Available System (BAS) methodology using LCA and LCC.
2. By applying the BAS in a municipality, we found that it is able to assess ELP and cost of current MSW treatments. Furthermore, the BAS' applicability is verified through a case study.

Moreover, through the case study, we found that it is necessary to understand ELP and cost of treatment processes so as to offer detailed improvement proposals for municipalities. Regarding ELP reduction, this study indicates that the cost will increase when the ELP decreases, which is conceptually comprehensible. However, this

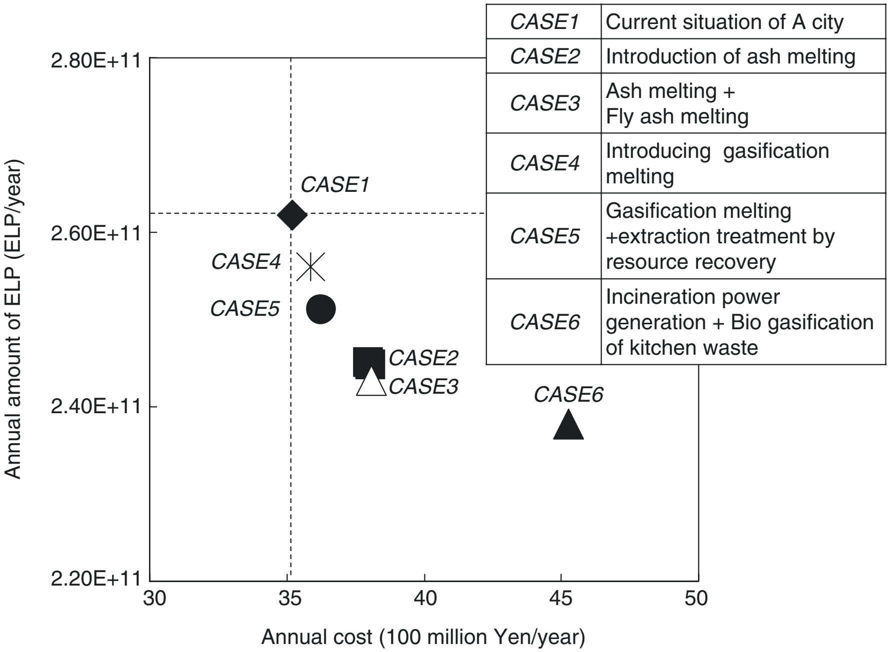

Fig. 8.6 ELP and cost in different cases

Table 8.11 ELP relative reduction effectiveness in each case

Case	2	3	4	5	6
ELP relative reduction effectiveness	−0.83	−0.90	−1.06	−1.43	−0.32

Table 8.12 Effect comparisons among specific index in each case (relative)

Case	ELP	Cost	Final disposal amount	Material amount	Energy recycling amount	CO_2 emissions
1 (current situation)	100	100	100	100	100	100
2	93	108	32	121	100	102
3	92	108	26	121	100	102
4	98	102	40	118	95	103
5	96	103	27	118	95	104
6	90	131	30	121	126	101

research provides quantitative data and emphasizes the significance of assessing the importance of recycling in more nuanced ways. Besides, with strained municipal finances, reducing the ELP and cost is a crucial issue. Hence, it is urgent and necessary to consider applying the BAS methodology so as to achieve the minimum cost and a society where recycling is the norm. We expect this debate to be resolved soon and the BAS methodology be selected among a large number of LCA evaluation approaches.

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Part II
Sustainable Manufacturing and 3R Technologies

Chapter 9
Life Cycle Assessment-Directed Optimization of Hydrogen Sulfide Removal During Biomass-Derived Hydrogen Production

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9.1 Introduction

Bio-resource utilization is currently being promoted by the Japanese government as a promising means of achieving an environmentally friendly society [1]. Hydrogen production in particular has attracted considerable attention as a means of slowing the progression of global warming [2]. However, the majority of hydrogen fuel currently produced is derived from fossil fuels, and therefore its production has a large environmental impact [3]. The use of biomass-derived hydrogen (Bio-H_2) is a promising means of reducing the negative impact of hydrogen production on the environment. Indeed, one private Japanese company is currently developing a small-scale (5–30 t/day) Bio-H_2 production plant that utilizes a biomass gasification process called the Blue Tower process [4].

Hydrogen fuel cells are a highly efficient means of converting the chemical energy of hydrogen directly into electricity. However, impurities mixed with the hydrogen in these fuel cells can reduce voltage output and shorten the lifespan of the fuel cell. Therefore, strict standards for the purity of hydrogen used in fuel cells have been published by the International Organization for Standardization; for example, the hydrogen used in the production of fuel cells for vehicles must have a purity of no less than 99.97% and contain no more than 0.2 ppm CO, 0.004 ppm H_2S, and 0.05 ppm halide as impurities [5]. Thus, efficient methods for removing such impurities from Bio-H_2 are needed.

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Synthesis gas (syngas) produced via the gasification of woody biomass contains as impurities mainly CO, H_2, CO_2, and CH_4 together with smaller amounts of sulfur, halogen gases, and other impurities. The amount of H_2S in this syngas is reported to be 50–230 ppmv H_2S [6]. In the Blue Tower process, when wood pellets were used as the raw feed material, the concentration of H_2S at the exit of the reformer of the gasifier is reported to be 48 ppm [4].

CO produced during the production of Bio-H_2 can be efficiently removed by using the steam shift reaction catalysts such as Fe/Cr or ZnO/CuO/Al_2O_3. For H_2S, metal oxides such as Zn and Fe can be used as adsorbents.

If a fuel cell system is to be used for transportation or as an energy supply, it is necessary to thoroughly evaluate the eco-burden posed by the manufacture and use of these materials. Recently, eco-indexes based on the life cycle assessment (LCA) methodology have been established in several European countries. These eco-indexes include not only CO_2 emissions on the basis of use phase but also other indexes such as impact categories. Renewable energy systems that harness chemical reactions have a large impact on abiotic depletion because rare metals are frequently used as catalysts. This means that when designing processes for the production of Bio-H_2, these eco-indexes, particularly CO_2 emission and abiotic depletion, must be taken into consideration.

In the present study, we examined the production of Bio-H_2 via biomass gasification by using the Blue Tower process, taking into consideration in the process design the consumption of rare metals as catalysts and the direct emission of CO_2 during operation. In addition, to balance quality and cost, the removal of impurities was also considered.

Desulfurization can be accomplished via either chemical or physical adsorption. Chemical adsorption by using a metal oxide has a high rate of adsorption, but it is difficult to regenerate the catalyst. In contrast, physical adsorption has a lower rate of adsorption due to van der Waals forces being weak adsorptive forces; however, the adsorbent remains active for a long time.

To address these problems, here we developed and tested a system that combines physical and chemical adsorption for the removal of H_2S during the production of Bio-H_2 (Fig. 9.1). Then, based on the results of that study, we designed a Bio-H_2

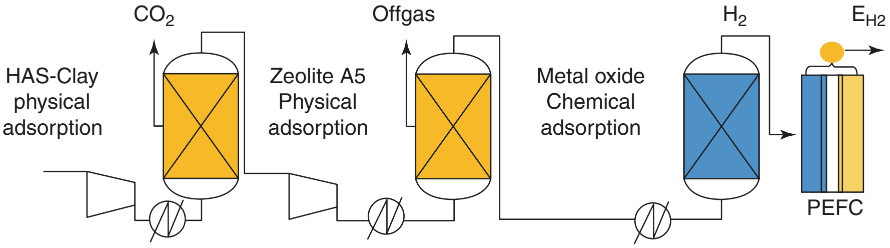

Fig. 9.1 Schematic diagram of the novel H_2S removal system

production process that included the optimized H_2S removal system. The environmental impact of our novel system was then assessed by means of LCA.

9.2 Experimental

9.2.1 *Chemical Adsorbents*

Zinc oxide (ZnO; HiFUEL A310; Alfa Aesar) and iron oxide (Fe_2O_3; Toda Kogyo Corp.), which are low-temperature H_2S adsorbents [7], and nickel(II) oxide (NiO; Toda Kogyo Corp.) and CaO (Kanto Chemical Corp.), which are high-temperature H_2S adsorbents, were prepared [8]. Prior to preparation, the adsorbents were passed through a sieve to ensure particle diameters of 2.2–3.35 mm.

9.2.2 *Physical Adsorbents*

Zeolite A-5 (Wako Pure Chemical Industries, Ltd.) and HAS-Clay (hydroxyl aluminum silicate clay; Toda Kogyo Co., Ltd.) were used as physical adsorbents. HAS-Clay is an amorphous aluminum hydroxide silicate ($SiO_2/Al_2O_3/H_2O$) that has excellent CO_2 absorptivity [9]. The particle size of zeolite A-5 was 2.36–4.75 mm, and that of HAS-Clay was 2.20–3.35 mm. The pore diameter of zeolite A-5 was 0.5 nm. HAS-Clay had a pore diameter peak of 0.02 nm and a specific surface area of 423 m^2/g. These adsorbents have been used as adsorbents in a two-step pressure swing adsorption (PSA) process to produce high-purity hydrogen at low pressure (0.4 MPaG) [9]. Therefore, this study evaluated that whether two-step PSA can adsorb H_2S simultaneously.

9.2.3 *Desulfurization Tests*

Figure 9.2 shows a schematic of the fixed-bed reactor used for the H_2S adsorption process. The reactor tube was made of stainless steel and had an outside diameter of 12.7 mm and an inside diameter of 10.7 mm. The adsorbent was packed on a sintered filter (φ10.0 mm × 3.1 mm) that was placed at the center of the tube reactor.

For the chemical adsorption test, the reactor was filled with N_2 and then heated to 40, 80, or 120 °C. Once the reactor had reached temperature, N_2 containing 83–100 ppmv H_2S was introduced to the reactor (gas flow rate, 250 mL/min; space velocity, 8784 or 25,287 h^{-1}; standard pressure).

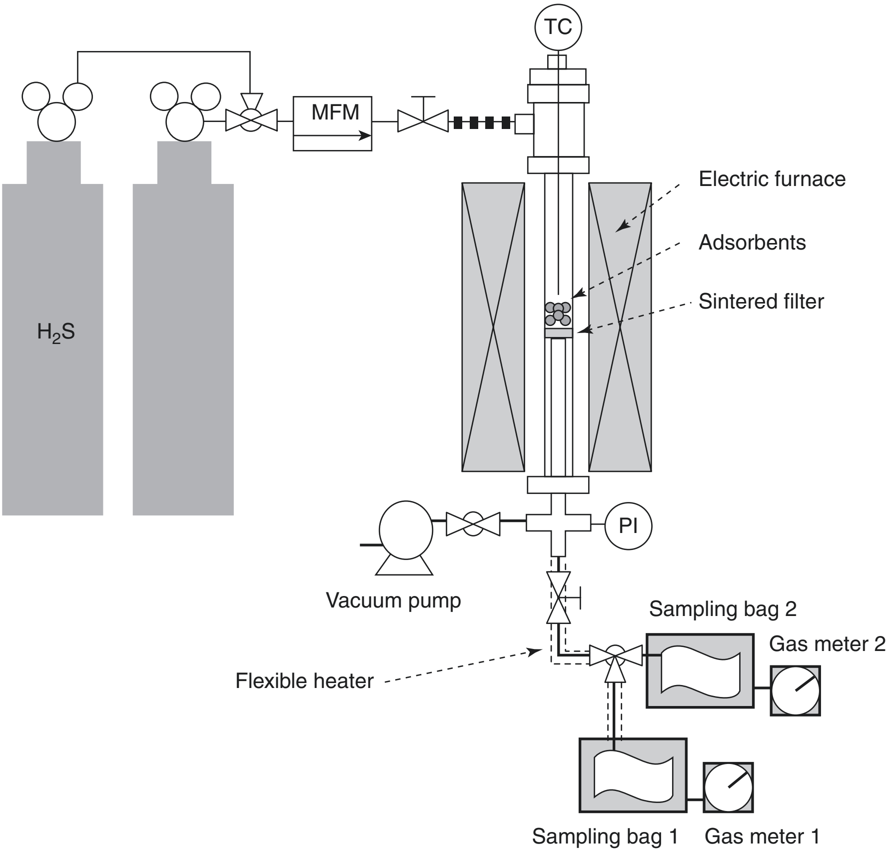

Fig. 9.2 Desulfurization test apparatus

Table 9.1 Composition of the syngas for physical adsorption tests

	Adsorbents	H_2	CO (%)	CH_4 (%)	CO_2	H_2S (ppm)
1	HAS-Clay	0.0%	0.0	0.0	Balance	30
2	HAS-Clay	Balance	0.0	9.0	17.6%	30
3	Zeolite A-5	0.0%	0.0	0.0	Balance	30
4	Zeolite A-5	Balance	23.0	9.0	0.0%	30
5	Zeolite A-5	Balance	23.0	9.0	1.0%	30

For the physical adsorption test, the reactor was filled with nitrogen N_2 and then heated to 40 °C. Once the reactor had reached temperature, syngas of one of the compositions shown in Table 9.1 was fed into the reactor (gas flow rate, 50 mL/min; space velocity, 2916 or 3888 h^{-1}; pressure, 0.4 MPaG).

After passing through the reactor, the off-gases were collected every 30 min in a gas-sampling bag placed in one of two sampling boxes (Fig. 9.2).

When the experiment was complete, the stream of N_2 containing H_2S or syngas was switched to a stream of N_2, the electric furnace was turned off, and the cover of the furnace was opened for cool down.

9.2.4 Gas Analysis

Sampled gases were analyzed by using a gas chromatograph equipped with a flame photometric detector (GC-8A; Shimadzu Corporation) and a packed column (Sunpak-S 80-100 E-9550; Shinwa Chemical Industries Ltd.). The initial and final gas chromatograph oven temperatures were set at 80 °C. The limit of detection of the flame photometric detector was 0.6 ppmv. Breakthrough curves were constructed by plotting H_2S concentration versus operating time. Breakthrough time was defined as the time from the start of operation to the time when the H_2S gas concentration collected at the sampling bag reached 1 ppmv.

9.2.5 Effectiveness of the Chemical Adsorbents

Figure 9.3a shows the breakthrough curve when ZnO was used as the adsorbent. The concentration of H_2S at each time point was within 1 ppmv at all three temperatures, suggesting that desulfurization performance was comparable at low and high temperatures. Regarding the gas components of 8 ppmv H_2S, 34.4% H_2, 20% H_2O and the balance of N_2, it is shown that the H_2S concentrations at different temperatures are various between 100 and 700 °C on basis of the thermodynamic equilbirium calculations [7]. These calculations also showed that under 400 °C the outlet gas would contain less than 1 ppmv of H_2S, whereas at temperatures over 400 °C it would contain more than 1 ppmv H_2S.

Figure 9.3b shows the breakthrough curve when Fe_2O_3 was used as the adsorbent. A clear temperature dependence was observed; the breakthrough point at 80 or 120 °C was much later than at 40 °C. Next, we calculated the thermodynamic equilibrium composition of the Fe_2O_3-FeS_2-H_2O-H_2S system by using the Aspen Plus software V8.8 as the simulating and modeling tool (Fig. 9.4). In the calculation, REquil was used to determine the thermodynamic equilibrium composition, and the initial concentrations were 100 ppmv for H_2S with N_2 balance. The thermodynamic equilibrium composition of H_2S was calculated to be 0.0 ppmv at 40–120 °C.

Figure 9.3c shows the breakthrough curve when CaO was used as the adsorbent. Although CaO adsorbents have the best performance at 500 °C [10], they adsorbed little sulfur at 40–120 °C, as demonstrated in the results of thermodynamic calculations [11].

Figure 9.3d shows the breakthrough curve when NiO was used as the adsorbent. A clear temperature dependence was observed; the H_2S-removal performance was better at 40 °C than at 120 °C. Although NiO had a lower H_2S-removal performance

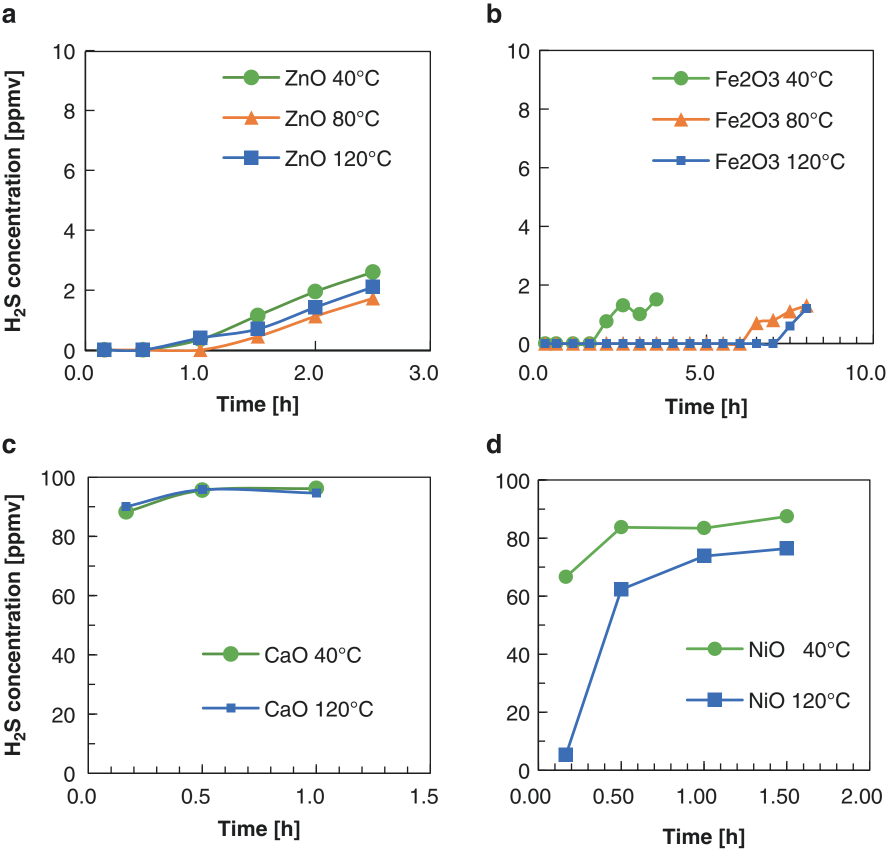

Fig. 9.3 Breakthrough curves of (**a**) ZnO, (**b**) Fe_2O_3, (**c**) CaO, and (**d**) NiO

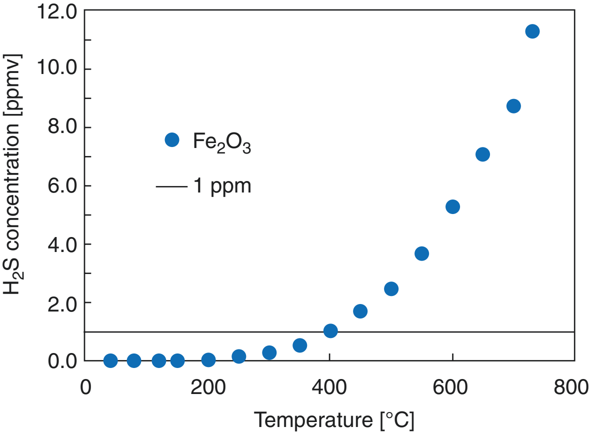

Fig. 9.4 Thermodynamic equilibrium composition of H_2S at different temperatures in the Fe_2O_3-FeS_2-H_2O-H_2S system

Table 9.2 Sulfur capacity of the chemical adsorbents

Temperature (°C)	ZnO		Fe_2O_3
40[a]	0.20		0.45
80[a]	0.26		1.38
120[a]	0.24		1.42

[a] Sulfur capacity = g-S/100 g-sorbent

than ZnO and Fe_2O_3 at 40 and 120 °C, it functions as a H_2S remover by means of catalyst poisoning [12], and during high-temperature desulfurization, it forms a liquid sulfide [13]. Therefore, the use of NiO-based adsorbents for the removal of sulfur warrants further investigation in the future.

Next, the sulfur capacity (S_{cap}, g-S/100 g-sorbent) of the ZnO and Fe_2O_3 adsorbents was calculated using

$$S_{\mathrm{cap}} = \frac{t_{\mathrm{BT}} \times \dot{V} \times C_{\mathrm{H_2S}} \times 32.07 \times \left(6 \times 10^{-4}\right)}{V_{\mathrm{m}} \times W_{\mathrm{sorbent}}}, \tag{9.1}$$

where t_{BT}, $\dot{V}$, C_{H_2S}, V_m, and $W_{sorbent}$ are the breakthrough time (min), flow rate of gas containing H_2S (L/min), H_2S concentration (ppmv), molar volume (22.4 L/mol under standard conditions), and adsorbent weight (g), respectively (Table 9.2). Fe_2O_3 had a larger sulfur capacity than ZnO at all three temperatures, suggesting that Fe_2O_3 is the most suitable adsorbent for the removal of H_2S at low temperatures.

9.2.6 *Effectiveness of the Physical Adsorbents*

Next, we examined the use of two physical adsorbents for the removal of H_2S under five different conditions. On the adsorption performance of HAS-Clay, the excess CO_2 gas was used (Case 1), and the sample syngas through the gasification process was tested (Case 2). Likewise, on the zeolite A-5, the following tests were executed (Cases 3–5). In Case 3, the excess CO_2 gas was used, and the sample gases with CO_2 concentrations of 0% and 1% based on the study of two-step PSA were tested in Cases 4 and 5 [9]. Note that the gas components in each case are shown in Table 9.1.

In order to investigate the influence of CO_2 on H_2S adsorption of HAS-Clay, Case 1 is a test conducted in the state of excess CO_2. On the other hand, in Case 2, an adsorption test of H_2S was performed using a gas composition produced by gasification. Note that, in Case 2, it is a composition that does not contain CO because of gas purchase problems. First, the use of HAS-Clay under conditions of excessive CO_2 and a gas composition produced by gasification were examined (Case 1, 2). In Case 1, it took longer to increase the outlet concentration of H_2S compared with Case 2 (Fig. 9.5a). This is because HAS-Clay readily and selectively adsorbs CO_2.

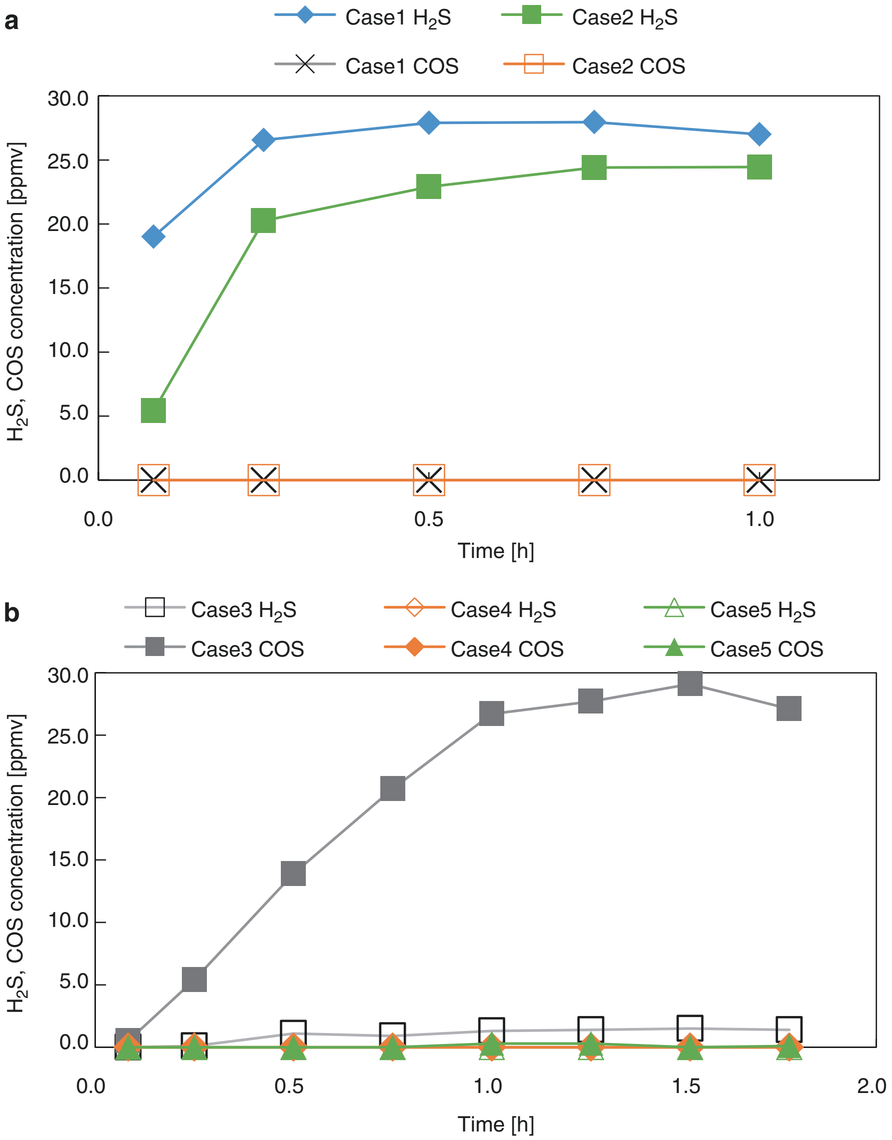

Fig. 9.5 Breakthrough curves for (**a**) HAS-Clay (Cases 1 and 2) and (**b**) zeolite A-5 (Cases 3, 4, and 5)

Next, in order to investigate the influence of CO_2 on H_2S adsorption of HAS-Clay, Case 3 is a test conducted in the state of excess CO_2. When zeolite A-5 was used and a supply gas containing H_2S/CO_2 = 30 ppmv/balance was used (Case 3), the following reaction was observed to have taken place:

$$H_2S + CO_2 \leftrightarrow COS + H_2O \tag{9.2}$$

Under the conditions of Case 3 (excess CO_2), COS was detected at 5 min after the start of the breakthrough test, and H_2S was detected at 15 min (Fig. 9.5b). The concentration of COS increased with time, eventually reaching 30 ppm. This result is consistent with a report by Lutz et al. showing that zeolite acts as a catalyst and COS and H_2O are produced from H_2S and CO_2 [14]. However, for the production of Bio-H_2, the generation of COS is undesirable because COS is difficult to remove. Therefore, to prevent the generation of COS, CO_2 must be removed. In a two-stage PSA process, it is possible to separate and recover 99.7% of CO_2 by using HAS-Clay as the adsorbent, which should minimize the production of COS for the production of Bio-H_2 [9]. Thus, we examined the effect of changing CO_2 concentration on COS concentration (Cases 4 and 5). Case 4 and Case 5 were experimented by changing the CO_2 concentration to 0% and 1% based on the gas composition of the study of two-step PSA [9]. When CO_2 was not present (Case 4), very little H_2S and COS were detected. When a trace amount of CO_2 was present, a slight amount of COS was detected in the middle stage of the observation period, but no H_2S was detected (Fig. 9.5b).

9.3 Process Modeling

The results of the adsorption experiment (Sect. 9.2) suggested that a two-step PSA process may be effective for the removal of H_2S in the production of Bio-H_2. Therefore, we designed and modeled two Bio-H_2 production processes, one incorporating a conventional PSA process (System S1) and one incorporating a two-step PSA process (System S2).

9.3.1 System S1

System S1 (Fig. 9.6a) comprised a gasifier, a water-gas shift reactor, and a desulfurizer in the middle of the temperature zone, and it incorporated a conventional PSA process.

The gasification reactor was the indirect-type, moving bed, gasification reactor (pyrolyzer, reformer, and preheater) that is used in the Blue Tower process. In this gasification reactor, alumina balls (heat career, HC) are circulated to supply heat to the reactor, which is warmed up to 1050 °C in a preheater, and HC circulates with the furnace of the reformer and the pyrolyzer. The operating temperature of the pyrolyzer is 550 °C, and that of the reformer is 950 °C at almost standard pressure (see [4] for more details of the Blue Tower process.).

The water-gas shift reactor comprised two reactors: a high-temperature shift (HTS) reactor with an inlet temperature of 350 °C and a low-temperature shift (LTS) reactor with an inlet temperature of 190–210 °C. Together, these reactors promote the water shift reaction (Eq. 9.3) and produce a gas rich in H_2:

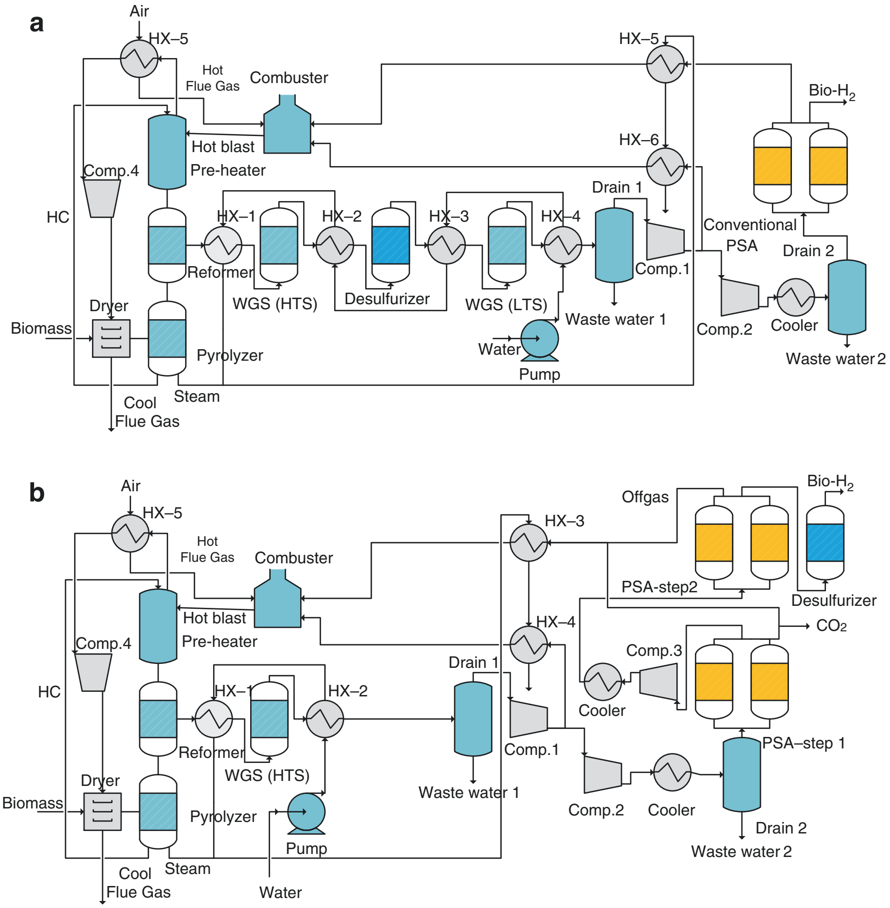

Fig. 9.6 Schematic of two designed Bio-H_2 production processes, one using a conventional PSA (**a**) and one using a two-step PSA process (**b**)

$$CO + H_2O \leftrightarrow H_2 + CO_2 \tag{9.3}$$

Fe/Cr-based catalysts are most often used in HTS reactors, and CuO/ZnO-based catalysts are most often used in LTS reactors. Fe/Cr-based catalysts are generally unaffected by the presence of impurities; therefore, contamination with H_2S can be tolerated to some extent. However, CuO/ZnO-based catalysts can become covered with H_2S at concentrations that do not affect Fe/Cr-based catalysts [15]. Therefore, it is necessary to remove H_2S from the gas prior to it entering the LTS reactor.

In the desulfurizer, although various H_2S adsorbents can be used, we decided to use ZnO, which has a maximal adsorption capacity at around 300 °C [7]. For this reason, the desulfurizer was installed between the HTS and LTS reactors [16].

In this process, a conventional PSA process with an operating pressure of 0.9 MPaG was used. A compressor is used to raise the pressure up to 0.9 MPaG, and the electric power used at that time is large. And the proportion of compressed power occupied by the auxiliary power of the plant was large. H_2 purified by a conventional PSA process has a purity of 99.99%. Also, the off-gas from PSA is used to warm the HC (heat career). The off-gas is burned in the combustor, and the preheater uses the heat of the exhaust gas of the combustor to heat the HC. If the heat is insufficient, part of the syngas that has passed through the drain at the end of the LTS reactor is sent to the combustor.

9.3.2 System S2

System S2 (Fig. 9.6b) comprised an indirect gasifier, a water-gas shift reactor, and a desulfurizer, and it incorporated a two-step PSA process. The gasification reactor was the same as that used in System S1. However, unlike in System S1, a two-step PSA process was used in System S2. We were able to reduce the amount of metal oxide used compared with a conventional desulfurization system by removing H_2S via the reversible two-step PSA process. Therefore, we installed the desulfurizer after, rather than before, the PSA unit to adsorb any H_2S that was not removed during the two-step PSA process. The results of our desulfurization tests (Sect. 9.2) suggested that Fe_2O_3 had high H_2S adsorption activity at low temperatures, so Fe_2O_3 was used as the adsorbent in the desulfurizer.

One further difference in System S2 is because the LTS catalyst is easily poisoned by H_2S (see Sect. 9.3.1), we only installed an HTS reactor in this system.

9.3.3 Modeling

Next, we simulated operation of the two systems by using the Aspen Plus on the assumption that the scale of the plant was 15 t/day and that the biomass material used was cedar waste material with a water content of 20 wt%. The chemical composition of the dry biomass is shown in Table 9.3. Operating temperature,

Table 9.3 Chemical composition of dry cedar wood [17]

Carbon [wt.%]	46.660
Hydrogen [wt.%]	5.480
Nitrogen [wt.%]	0.120
Oxygen [wt.%][a]	47.351
Ash [wt.%]	0.389
Volatiles [wt.%]	86.210
Higher heating value [kJ/kg]	18.348

[a] Oxygen by difference

Table 9.4 Operating conditions

	Case 1	Case 2
Gasifier (Blue Tower process)		
Plant scale (wet basis)	15	15
Pyrolysis zone [°C]	550	550
Reforming zone [°C]	950	950
Circulation rate of heat carrier [kg/kg-feedstock]	6.34	6.34
Steam-to-carbon ratio [–]	1.0	1.0
Operating pressure [MPaA]	0.106	0.106
Reformer (HTS/LTS)		
Operating temp. (HTS) [°C] (iron/chromium catalyst)	350	350
Operating temp. (LTS) [°C] (copper/zinc catalyst)	240	–
Desulfurizer		
Operating temp. [°C] (ZnO adsorbents)	300	
Operating temp. [°C] (Fe_2O_3 adsorbents)		30
PSA (conventional)		
Operating pressure [MPaG]	0.8	
H_2 recovery eff. [%]	73.9	
PSA (two-step)		
Operating pressure [MPaG]		0.4
H_2 recovery eff. [%]		56.0
CO_2 recovery eff. [%]		97.5

steam-to-carbon ratio, approach temperature difference, and composition of the pyrolysis gas were set as described in a study by Dowaki et al. (Table 9.4) [17].

Conventional components included in this simulation were H_2, CO, CH_4, CO_2, C_2H_2, C_2H_4, C_2H_6, H_2O, H_2S, NH_3, and char. To simplify the simulation, char was assumed to consist of solid carbon. For sulfur, again referring to a study by Dowaki et al., the concentration of H_2S at the exit of the reformer was set at 50 ppm [4].

RYield block was used for the pyrolyzer, and the syngas components of the feedstock at 20% moisture were represented as in Eq. (9.4) [17].

$$\begin{aligned}&C_{31.078}H_{43.495}O_{23.677}N_{0.069}+31.078H_2O\rightarrow\\&29.946H_2+14.508CO+0.255CH_4+8.796CO_2\\&+6.109\times10^{-5}NH_3+21.694H_2O+0.029N_2\\&+\mathrm{Char}\left(C_{2.866}H_{0.482}O_{0.343}N_{0.004}\right)\end{aligned}\tag{9.4}$$

The reformer and HTS and LTS reactors were simulated with REquil block, and the PSA process and desulfurization reactor were simulated with separator block.

HeatX block was used for the preheater and for all heat exchangers, which were assumed to be countercurrent, and heat loss was assumed to be 5.0% of the sensible heat at the input flow. The combustor was simulated with RStoic block. The isentropic and mechanical efficiencies of the compressors were 80% and 81%, respectively.

The overall system performance was evaluated by using the simulation results to calculate the energy efficiency (η) as follows:

$$\eta = \frac{\dot{E}_{\mathrm{H_2}}}{\dot{E}_{\mathrm{biomass}} + \dot{E}_{\mathrm{elect}} + \dot{E}_{\mathrm{steam}} + \dot{E}_{\mathrm{air}}} \tag{9.5}$$

where $\dot{E}_{\mathrm{biomass}}$, $\dot{E}_{\mathrm{elect}}$, $\dot{E}_{\mathrm{steam}}$, and $\dot{E}_{\mathrm{air}}$ are the flow rates of the energy of biomass, electricity, steam, and air, respectively. The energy efficiency of System S1 and System S2 was 43.4% and 42.6%, respectively. In System S2, CO_2 could be effectively removed without markedly affecting efficiency.

9.4 Life Cycle Assessment

Next, we conducted an environmental assessment of Bio-H_2 production, including items such as the collection and transportation of raw materials, Bio-H_2 production, auxiliary power at the plant, and the influence of catalysts and adsorbents, by using the LCA method.

9.4.1 Definition of the System Boundary

A small-scale (raw material 12-t dry biomass/day) Bio-H_2 production plant using a dispersed, indirect gasification process and cedar wood as the raw material was assumed. According to Hashimoto et al., a plant of this size is able to collect biomass from within an area up to 50 km from the plant [18]. To evaluate the influence of factors such as catalyst and adsorbent choice on Bio-H_2 production, we examined two processes, one using a conventional PSA process (Case 1) and one using a two-step PSA process (Case 2). The functional unit was 1 Nm^3 Bio-H_2 (purity, 99.99 vol%), and the reference flow was 1-kg dry biomass. For the evaluation range, the well-to-tank approach was used. After biomass was collected, it was assumed to be chipped, transported to the plant (Subsystem1, SS1), and used immediately for the production of Bio-H_2 (SS2, syngas production; SS3, separation and cleaning). Capital goods were excluded from the evaluation (Fig. 9.7).

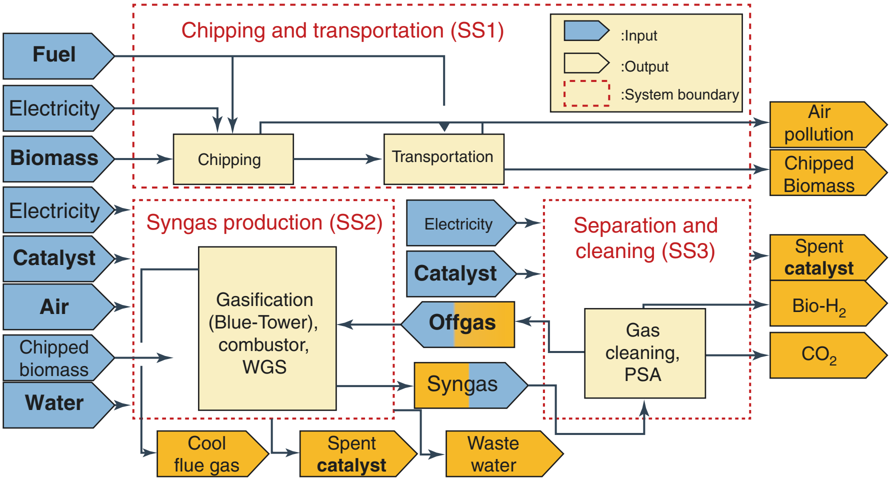

Fig. 9.7 System boundary

9.4.2 *Raw Material, Chipping, and Transportation to the Plant (SS1)*

For the raw cedar wood, data for coniferous waste wood in the ecoinvent 3.2 database was used as the background data. According to research by Watanabe et al., the energy consumption for the chipping of cedar wood is 1.033 g/kg-feed for a diesel oil-based wood chipper and 0.0136 kWh/kg-feed for an electric wood chipper [19]. In addition, the biomass can be transported from within a range of 5–50 km; the midpoint of this range (i.e., 27.5 km) was used in the simulation.

9.4.3 *Bio-H_2 Production System (SS2, SS3)*

The Bio-H_2 production system was designed by using Aspen Plus® V8.8. Two conditions were evaluated for Case 1 as system S1 and Case 2 as system S2 (see Sect. 9.3, Fig. 9.6). During the production of Bio-H_2, CO_2 is produced as a byproduct when the gas is purified in the first stage of the two-step PSA process. Since CO_2 can be used by farms to fertilize plants, we did not consider CO_2 to be an environmental emission, and it was not considered to have an impact on the environment. For the inventory data, in addition to using the simulation results, formulae (9.6) and (9.7) and the results of the adsorption experiment (see Sect. 9.2) were used to determine the optimal amounts of catalyst and adsorbent:

$$W_{\mathrm{catalyst}} = \frac{\dot{V} \times 10^{-6}}{\mathrm{GHSV}} \times \rho_{\mathrm{catalyst}} \tag{9.6}$$

Table 9.5 Inventory data for 1 Nm^3 Bio-H_2 production

	Case 1	Case 2
Input from nature		
Air (SS2) [kg]	18.37	20.77
Input from technosphere		
Cedar (wet) (SS1) [m^3]	1.3.E−02	1.3.E−02
Diesel (SS1) [g]	74	76
Electricity (SS1) [kWh]	2.4.E−02	2.5.E−02
Water (SS2) [kg]	0.64	0.66
HTS-catalyst (SS2) [kg]	1.2.E−06	1.2.E−06
LTS-catalyst (SS2) [kg]	6.1.E−05	–
Electricity (SS2) [kWh]	0.32	0.33
Adsorbents (SS3)		
Case 1 desulfurization [kg]	9.8.E−04	
Case 2 desulfurization [kg]		2.3.E−05
Electricity (SS3) [kWh]	0.32	0.31
Emission to the environment		
SO_2 (SS2) [kg]	2.9.E−07	3.0.E−04
CO_2 (SS2) [kg]	2.5	0.8
Waste water (SS2) [kg]	0.20	0.24

$$W_{\text{adsorbent}} = \frac{\dot{V} \times C_{H_2S} \times 32.07 \times \left(6 \times 10^{-4}\right)}{V_m \times S_{\text{cap}}} \tag{9.7}$$

where W_{catalyst}, $W_{\text{adsorbent}}$, $\dot{V}$, ρ_{catalyst}, GHSV, C_{H_2S}, and V_m are the amount of catalyst (kg), amount of adsorbent (kg), gas flow rate (mL/h), catalyst bulk density (kg/m^3), gas hourly space velocity (h^{-1}), H_2S concentration (ppmv), and molar volume (L/mol), respectively. The inventory data results are shown in Table 9.5.

9.5 Environmental Impact Assessment

To assess the environmental impact of the two Bio-H_2 production systems, analysis up to the midpoint 11 impact categories was conducted by using the Centrum voor Millieukunde Leiden (CML) method, and the results were calculated by using SimaPro 8.2 software. Background data were obtained from the ecoinvent 3.0 database. The results for Case 1 and Case 2 are shown in Table 9.6, and a comparison of these results is shown in Fig. 9.8.

In Case 1, where a conventional PSA process was used, syngas production was found to dominate all of the impact categories except for abiotic depletion. This is because exhaust gases containing a large amount of CO_2 are released from the combustor. Abiotic depletion was dominated by separation and cleaning. In separation and cleaning, a large amount of ZnO adsorbent is used to remove H_2S, so it occupies a large proportion of abiotic depletion index.

Table 9.6 Life cycle assessment result for the production of 1 Nm^3 Bio-H_2

Impact category	Unit	Case 1	Case 2
Abiotic depletion	kg Sb eq.	7.68.E−06	7.07.E−07
Abiotic depletion	MJ	1.91.E+01	1.39.E+01
Global warming	kg CO_2 eq.	3.60	1.50
Ozone layer depletion	kg CFC-11 eq.	1.75.E−07	1.36.E−07
Human toxicity	kg b.w.[a]	2.20.E−01	1.48.E−01
Fresh water aquatic ecotoxicity	m^3 polluted water[a]	1.43.E−02	9.62.E−03
Marine aquatic ecotoxicity	m^3 polluted water[a]	6.18.E+02	3.57.E+02
Terrestrial ecotoxicity	kg polluted soil[a]	2.48.E−03	1.59.E−03
Photochemical oxidation	kg C_2H_4 eq.	3.22.E−04	2.30.E−04
Acidification	kg SO_2 eq.	6.59.E−03	4.64.E−03
Eutrophication	kg PO_4 eq.	5.99.E−04	4.35.E−04

[a] Polluted to a defined threshold level

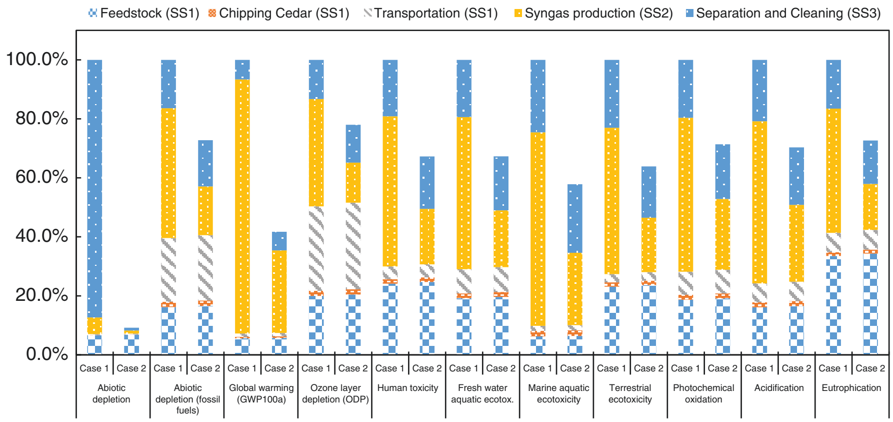

Fig. 9.8 Comparison of the life cycle assessment result for Case 1 and Case 2

In Case 2, where a two-step PSA process was used, the global warming proportion of syngas production was similar to that for feedstock and transportation, and both were small. Since the two-step PSA process removed most of the CO_2 produced, the amount of CO_2 in the exhaust gas released from the combustor was greatly reduced. Also, since the separated CO_2 can be used by farms to fertilize plants, the carbon can be fixed without being released as CO_2 into the atmosphere [9]. An improvement in abiotic depletion was also observed. This is because most of the H_2S was removed by physical adsorption, so less Fe_2O_3 was used to remove the remaining H_2S. Thus, it was possible to reduce the impact on abiotic depletion by 91% and global warming by 58%.

9.6 Conclusion

Here, we found that introducing a two-step PSA process into a Bio-H_2 production process reduced the amount of adsorbent required to remove H_2S and reduced the environmental burden of the entire Bio-H_2 production process.

In an experiment examining adsorption of H_2S at low temperatures, we found that Fe_2O_3 and ZnO were the most suitable chemical adsorbents. We also found that physical adsorption using a two-step PSA process with HAS-Clay and zeolite A-5 can remove H_2S to below the limit of detection of a gas chromatography—flame photometric detector.

By simulating a Bio-H_2 production process in which these changes were implemented, we showed that H_2S could be removed without reducing energy efficiency compared with a conventional process. Moreover, the impact of the overall production process on abiotic depletion was reduced by 91%, and the impact on global warming was reduced by 58%, suggesting that our novel system would have less impact on the environment than do systems currently in operation.

The present study suggests advantages of using a two-step PSA process in the production of Bio-H_2. In order to carry out a more detailed evaluation of PSA, it is necessary that PSA will be subjected to dynamic simulation, which concerns unsteady operations in the future. In addition, if the necessary physical property values for performing unsteady analysis are not sufficient, physical property data is obtained from experiments, and unsteady analysis is planned based on the physical property values.

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Chapter 10
Sustainable Application of Biopolymer

Shih-Chen Shi, Jhen-Yu Wu, Teng-Feng Huang, and Yao-Qing Peng

10.1 Introduction

While continuously making our lives more convenient, developments in technology should also ensure high standards for other aspects of human life, for example, a benign environment, clear sun, unpolluted air, clean water, and good tree phytoncide. Therefore, popular trends in scientific research, as we can observe, involve energy saving, carbon emission reduction, natural resource conservation, and waste reduction [1–3]. Specific in our research, the aim is to achieve energy saving and carbon emission reduction through the development and use of novel energy technologies, i.e., introducing creature and environment-friendly biopolymer materials that can naturally decompose to replace traditional petrochemical- and mineral-based materials, among which the replacement of plastic products is particularly critical. They exist everywhere in our daily life, appearing in advertisement boards, bags, or even small particles in facial cleansers. Indecomposable by the environment in a short period of time, they pose great damage to the ecological system of the earth; this is especially harmful for marine creatures and coastal birds. Therefore, it is necessary and urgent to develop green material technologies that can produce environmentally benign, naturally decomposable, industrial materials (with the purpose of replacing existing plastic materials and semiconductor substrates). Through ceaseless efforts in this area, our hope is to realize the goal of "from earth, to earth." There are primarily two approaches to tackle the problem of plastics: one is to recycle, and the other is to use biologically decomposable materials. The focus of the present study is to assess the potential and feasibility of replacing plastic products with biopolymers through a series of investigations of material properties and SWOT analysis.

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The material properties investigated for the studied biopolymer HPMC include its biocompatibility, self-healing, anticorrosion, tribological performance, and wear behavior. The ultimate objective of this work is to contribute to sustainable management of the earth.

10.2 Experimental Setup

10.2.1 Biocompatibility

Fertilized zebrafish embryos were incubated HPMC solution with various concentrations upon embryogenesis and until 72 h postfertilization (hpf). The HPMC solutions were prepared with 0.3× Danieau buffer with 1× penicillin/streptomycin (Gibco) for different concentrations. The HPMC solutions for the incubation were clean and changed every 24 h. The embryos' properties were recorded at different developmental stages. The incubation temperature was kept at 28 °C during the entire experiment. The HPMC-treated zebrafish embryos were anesthetized using 0.16 mg/mL tricaine (3-amino benzoic acid ethyl ester, Sigma) during photography and were then released into the incubation medium.

10.2.2 Film Preparation

Hundred milliliter ethanol was heated to 60 °C using a magnetic stirrer on a hot plate, and 30 mL water and 5 g of hydroxypropyl methylcellulose (HPMC), hydroxypropyl methylcellulose phthalate (HPMCP), and hydroxypropyl methylcellulose acetate succinate (HPMCAS) powder were then slowly added to it until complete dissolution. An MoS_2/HPMC composite film was prepared by adding 4 g additive (MoO_3, fullerene-like (IF) MoS_2, hexagonal (2H) MoS_2) powder into the HPMC solution and then extracting 150 μL of the mixed solution with a micropipette after 20 min of ultrasonication and dropping it onto a silicon substrate and keeping the sample at room temperature to dry for 1 h.

10.2.3 Self-Healing

The first step of the self-healing experiment was to create a circular wear scar on the film in the pin-on-disk wear process, after which a healing treatment was performed to smoothen this wear scar. Here, the healing treatment specifically refers to the process of adding drops of liquids such as deionized water, methyl alcohol, ethyl alcohol, and acetone on a HPMC dry coating that had a circular wear scar generated by a wear test. Then, the effects of the healing treatment on the tribological properties of HPMC could be assessed from post-healing tribotest results.

10.2.4 Anticorrosion

The corrosion potential and corrosion current of the films were electrochemically measured using the potentiodynamic polarization (PP) method.

10.2.5 Tribological Performance

Tool grade hard chrome steel balls (AISI 52100, diameter 2.38 mm) with an average roughness of 20 nm (Ra) were used as counter ball. Tribotests were conducted on the rotary ball-on-disk tribometer (POD-FM406-10NT, Fu Li Fong Precision Machine, Kaohsiung, Taiwan). The wear-tester was nominally identical to the ones reported in previous works. During the tribotest, under an applied force of 2 N and real contact pressure of 20 MPa, a sliding distance (one cycle) equal to 6.28 mm and sliding speed of 1–10 mm/s were measured at room temperature with a relative humidity of 50–70% under dry sliding conditions. The applied normal force was set to 2 N to observe the wear behavior. The wear rate (wear scar) observations were then used to quantify the wear volume by a 3D laser scanner (VK9700, Keyence, Osaka, Japan).

10.2.6 Property Analysis

The surface morphology of the material was observed using scanning electron microscopy (SEM) and transmission electron microscopy (TEM), whereas the structure and surface bonding of the material were analyzed using Fourier transform infrared (FTIR) spectroscopy and Raman spectroscopy.

10.3 Results and Discussion

10.3.1 SWOT Analysis for Biopolymer Application

Table 10.1 shows the results of the SWOT analysis for biopolymer applications.

Table 10.1 SWOT analysis for biopolymer application

Strength: 1. Pollution-free as tree fiber materials are from and eventually return to nature. 2. Addresses global concern on environmental protection. 3. Findings and experience from previous studies: good biocompatibility, self-healing and anticorrosion properties, and tribological performance. 4. Easy processing: spin coating, spraying technology.	*Weakness*: 1. Property limitations as they are natural materials. 2. Resistance to temperature variation. 3. Price/performance compared to that of petroleum-based lubricant.
Opportunity: 1. Need for sustainable manufacturing (tribology). 2. Replacement for resin products. 3. Increasing demand in multifunctional films (e.g., anti-wear + conductivity, energy efficiency + anticorrosion).	*Threat*: No threat

Table 10.2 Length of fish body after 72 h incubation

Fish no.	1% HPMC	0.5% HPMC	Wild
1	3.536	3.312	3.671
2	3.682	3.544	3.579
3	3.605	3.606	3.458
4	3.558	3.278	3.061
5	2.976	3.285	3.301
6	3.268	3.387	3.625
7	2.852	3.483	3.500
8	3.444	3.423	3.901
9	3.403	3.368	3.164
10	3.353	3.375	3.680
11	3.018	3.550	3.717
12	3.384	3.539	3.566
13	3.317	3.446	3.584
14	3.463	3.419	3.503
15	3.457	3.374	3.790
16	3.286	3.390	3.394
17	3.655	3.478	3.394
18	3.579	3.549	2.536
19	3.524	3.326	3.639
20	3.367	3.424	
21	3.358	3.553	
22	3.399		
Body length AVG	3.3856364	3.433761905	3.455526
STD	0.2127716	0.096732572	0.32663

10.3.2 Biocompatibility

The incubation and growth records of zebrafish embryos in the HPMC solution are shown in Table 10.2, where some data points are not included due to the length limit that applies to this paper. The experimental results show that, in terms of fish body

Table 10.3 Self-healing properties of HPMC

Self-healing	Reagent	Healing rate (%)	Healing efficiency (%)
External solvent	Water	93	98
	Methanol	85	40
	Ethanol	65	40
	Acetone	5	38
Ambient condition	Temperature	28	35
	Relative humidity	28	80
	Temperature + RH	40	65

length, no significant differences were observed in the embryos cultured in HPMC solutions and their wild counterparts, suggesting high biocompatibility of the HPMC material [4].

10.3.3 Self-Healing

The self-healing properties of HPMC are shown in Table 10.3 [5]. It can be seen from these results that under certain conditions, HPMC features excellent self-healing properties. The healing rate and healing efficiency are defined as follows:

$$\text{Healing rate}(\%) = 1 - \frac{\text{Wear volume after healing process}}{\text{Initial wear volume}}$$

$$\text{Healing Efficiency}(\%) = 1 - \frac{\text{Initial COF}}{\text{COF after healing process}}$$

10.3.4 Anticorrosion

The anticorrosion properties of two HPMC derivatives, HPMCP and HPMCAS, are shown in Table 10.4 [6].

10.3.5 Tribological Performance

The tribological performance of the film material is summarized in Table 10.5 [7–9], where the wear rate is defined as:

$$\text{Wear rate}(\%) = 1 - \frac{\text{Wear volume after healing process}}{\text{Initial wear volume}}$$

Table 10.4 Anticorrosion properties of HPMCP and HPMCAS

Material	Relative icorr (%)
HSS	100
HPMCP1 (200 μm)	26
HPMCP2 (400 μm)	20
HPMCP3 (600 μm)	3
HPMCAS1 (200 μm)	7
HPMCAS2 (400 μm)	5
HPMCAS3 (600 μm)	6

Table 10.5 Tribological properties of HPMC

Tribological performance enhancement	Wear rate (%)
Si	100
HPMC/Si	20
MoO_3/HPMC/Si	40
2H-MoS_2/HPMC/Si	25
IF-MoS_2/HPMC/Si	16
SA/HPMC/Si	2

Table 10.6 Analysis techniques for HPMC

Technique	Equipment	Characteristics studied
Electronic microscopy	SEM	Morphology
	TEM	Structure
Spectral analysis techniques	FTIR	Surface bonding
	Raman	Surface bonding, structure, element mapping

10.3.6 *Ease of Assessment*

As a polymer with crystallization property, HPMC can be readily assessed using various equipment, which is good for future mass production and material property monitoring during use [10, 11] (Table 10.6).

10.4 Summary

A SWOT analysis for the future use of biopolymer HPMC was conducted. Material properties of HPMC with respect to different application scenarios were tested. The following conclusions can be drawn from this work.

1. The SWOT analysis shows that biopolymers such as HPMC have the potential for practical application as a functional coating, which requires further research in the future.
2. With remarkable material properties, such as good biocompatibility, self-healing and anticorrosion properties, and tribological performance, HPMC can be utilized in various applications.
3. Online monitoring/analysis of the biopolymer materials using spectral techniques during film preparation shows potential for future mass production.

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Chapter 11
Implementation of an Energy Metering System for Smart Production

Friedrich A. Halstenberg, Kai Lindow, and Rainer Stark

11.1 Introduction

The term “Industry 4.0” is used for the fourth industrial revolution [1] and represents the convergence of industrial production and communication technologies. One of the important components of the Industry 4.0 is the Internet of Things (IoT) [2]. It allows “things”, such as RFID, actuators, sensors, etc., to interact and communicate with each other for reaching the common goals [3]. Furthermore, the smart factory is a particular implementation of CPS that is based on the extensive and deep application of information technologies to manufacturing [4].

In the era of Industry 4.0 and smart factories, machines become increasingly connected. By means of sensors, which play an increasing role in the smart production, the important production parameters can be measured and monitored. The performance of the production system—i.e. the continuous improvement and adjustments of production processes—occurs in particular by analysing and managing the supplied data by sensors.

Due to the ever-increasing demand for an energy-efficient manufacturing and in the context of smart production, energy metering systems become a driver to improve the energy consumption within all production processes. In reaction to this, the present article shows how an energy metering system has been planned and implemented on a smart factory demonstrator. First, measuring results from the system are presented and analysed, and suggestions for improvement of the production system are derived. A generic procedure for the implementation of the system is given in order to use it on further production systems.

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11.2 State of the Art

11.2.1 Digitization

The Industry 4.0 is defined as digitization of the manufacturing sector, with embedded sensors in virtually all product components and manufacturing equipment, ubiquitous cyber-physical systems and analysis of all relevant data [5]. In the context of Industry 4.0, digitization means that the information and communication technology enables the networking of people and things and the convergence of real and virtual world [6].

By using the right tools, digitization provides a plus in efficiency throughout all product life cycle phases. The conception and the design of the machine control can be tested earlier. Routines and checks take place earlier in the engineering process, which reduces the risk of failures and errors in critical phases of the life cycle, such as during commissioning, which previously could only be eliminated with great effort and under time pressure [7].

11.2.2 Smart Manufacturing and Industry 4.0

Smart manufacturing aims for integrating the intelligence of different entities such as the customer, partners of the general public into the enterprise. It acts coordinated and performance-oriented while minimizing energy and material usage and maximizing environmental sustainability, health and safety and economic competitiveness [8].

The Industry 4.0 is characterized by the availability and usage of data in real time. This concerns data of production, order and status of machines but also data of inventory. There are no restrictions. By means of cloud solution, these data are available worldwide and permanently up-to-date. Furthermore, the Reference Architectural Model Industrie 4.0 (RAMI 4.0, [9]) integrates the essential elements of Industry 4.0 in a three-dimensional layer model as shown in Fig. 11.1. Based on this scaffolding, industrial 4.0 technology can be systematically arranged and further developed. The model combines the different user perspectives and creates a shared understanding of industrial 4.0 technologies. RAMI 4.0 is a kind of 3D map for industrial 4.0 solutions: the model provides an orientation on which the requirements of the user industries are applied together with national and international standards to define and further develop Industry 4.0. Overlaps and gaps in standardization are thus visible and can be closed [9].

11.2.3 Digital Product Twins and Digital Factory Twins

The concept of the digital twin dates back to a University of Michigan presentation to industry in 2002 for the formation of a Product Lifecycle Management (PLM) Centre. It is based on the idea that a digital informational construct about

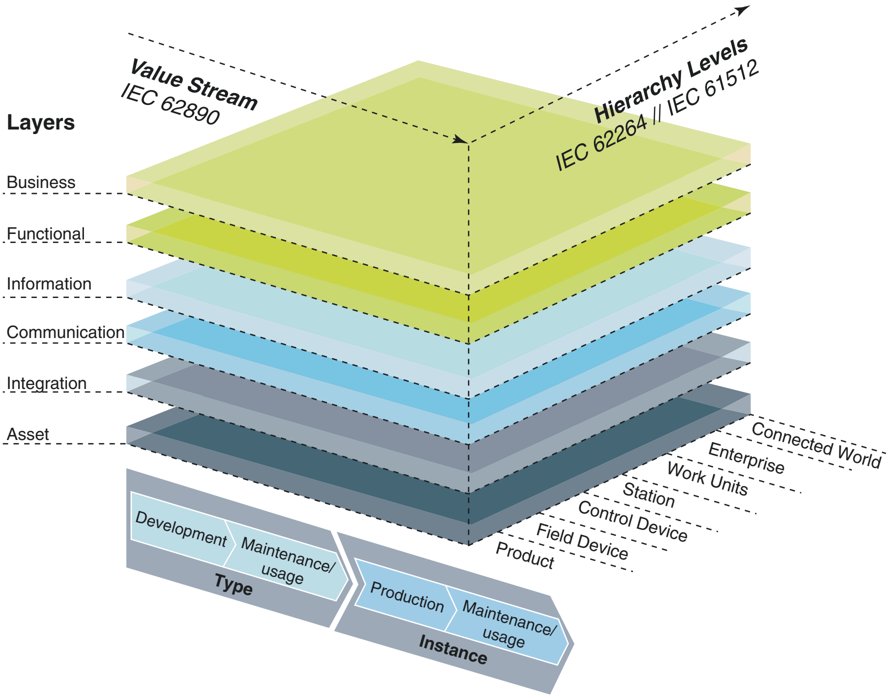

Fig. 11.1 Reference architecture model for Industry 4.0 [9]

a physical system could be created as an entity on its own. This digital information would be a "twin" of the information that was embedded within the physical system itself and be linked with that physical system through the entire life cycle of the system [10].

Industry 4.0 and the digitization of the manufacturing industry enable real and virtual world to grow together. This also means that every real physical product has a "digital twin", which always accompanies it everywhere. It is already born with the product idea, serves as a masterpiece in production and then grows further and further into the product development process and remains inseparably linked to it throughout the entire life cycle. New or modified plants can be put into operation virtually in advance, thus minimizing downtime during commissioning and reconfiguration. During the production process, digital twins support compliance with quality parameters or the planning and adherence to production sequences.

A digital twin is a digital representation of a unique product (real object, service or intangible asset) that comprises its properties, condition and behaviour by means of models, information and data. Every product produces a digital shadow by means of operation and condition data, process data, etc. Hence, a digital twin consists of a unique instance of the universal digital master model. The digital twin is also consisting of its individual digital shadow and an intelligent linkage (algorithm, simulation model, correlation, etc.) of the digital shadow and digital master [11]. This relation between the digital twin, digital master and digital shadow can be seen in Fig. 11.2.

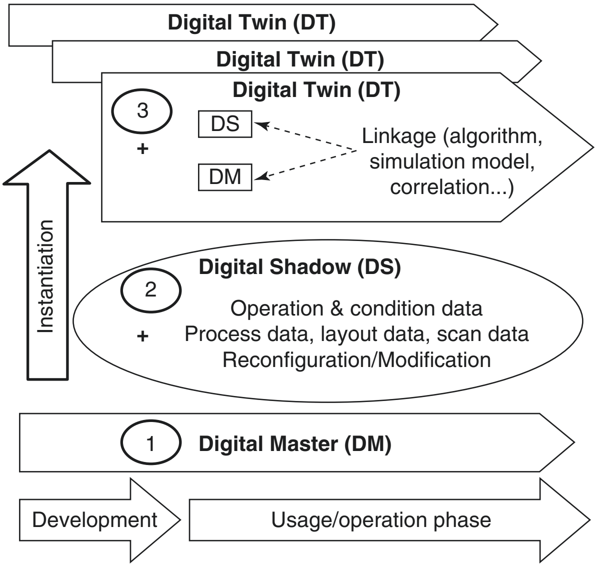

Fig. 11.2 Relationship between digital master (DM), digital twin and digital shadow (DS), based on [11]

Digital twin is the digital form of a real object. The basis is the CAD-3D model, which is assigned all product characteristics, functions and process parameters—from the material to the sensors, to movement and dynamics. As an intelligent 3D model, the digital twin can create a realistic simulation in a computer-supported environment. All aspects of operation and processes can be carried out in real time. This enables the start of programming, the optimization and testing of extreme situations before the availability of the individual components and modules. In short, commissioning is virtually possible even in the planning phase.

11.2.4 Energy Metering in Production Systems

It is widely acknowledged that the minimization of the energy consumption during production processes demands to quantify the amount of energy needed, to determine optimization potential. The benefits and limitations associated with implementing an energy measurement and quantification system in a smart manufacturing environment are rarely described in the literature [12, 13]. The implementation of an energy system of this kind has the potential to give absolute energy transparency and to create an overview of the energy consumption, to identify the production processes with optimization needs [13]. Nowadays in the era of Industry 4.0, a remote energy monitoring and controlling of smart factories could be easily built. Using onside non-invasive energy sensors, OPC server and web-based technology, the information of energy consumption of the manufacturing performance process along with the analysis and guidance can be sent to decision makers in the industries. It will help them to understand their energy use, take appropriate action and continually improve energy efficiency and manufacturing performance [14, 15].

11.3 The Demonstrator Cell "Smart Factory"

Achieving Industry 4.0 implies trying out new methods, concepts and technologies and skilfully mixing them with each other. For this purpose, the demonstrator cell "SmartFactory 4.0" has been developed. Mechanisms, use cases and potentials of smart data and of a digital twin factory for research and development partner can be here experienced and researched based on a batch size 1 production [16].

The demonstrator cell "SmartFactory 4.0" represents a production line, where all aspects of Industry 4.0 can be tested and optimized in a variety of ways. The objective is to demonstrate the information technology-related interactions and potentials of cyber-physical systems and digital twins for the industrial application and to develop strategies for their introduction into the company in cooperation with customers [16].

The "SmartFactory 4.0" functions with the scenario of the production of a drink coaster, which can be designed freely by the customer in shape, material and colour and is afterwards manufactured directly or remotely. The product, which the customer configures by means of a web-based interface, can be specified as a single part or as an assembly, resulting in different paths through the production. Starting from the product specification, fully automated product structure, process plan and control programs are generated. These include, among others, CNC programming with G-code for machining, part numbers on RFID chips, control of clamping devices, logistics and quality control processes as well as the derivation of the assembly plan [16].

Depending on the order, the raw parts are brought into the required shape in a milling station. A camera-based quality control unit checks product properties such as shape, dimensional accuracy, material and colour and sends defective parts back into the cutting process. At the same time, deviations continually flow back into the automatic G-code generation in order to achieve continuous improvement in production. Figure 11.3 shows the schematic representation of the demonstration cell including the associated modules [16].

After the individual part inspection, the parts are transported to the assembly workplace by means of an autonomous transport tracked robot, where they are assembled with the help of dynamically generated mounting instructions by the installer via display, head-up display or pick-by-light. The assembly result is, however, checked for quality, transferred to the dispensing station and then sent to the removal station after identification of the customer. From the beverage coaster designed by the customer, this becomes an intelligent product that is equipped with

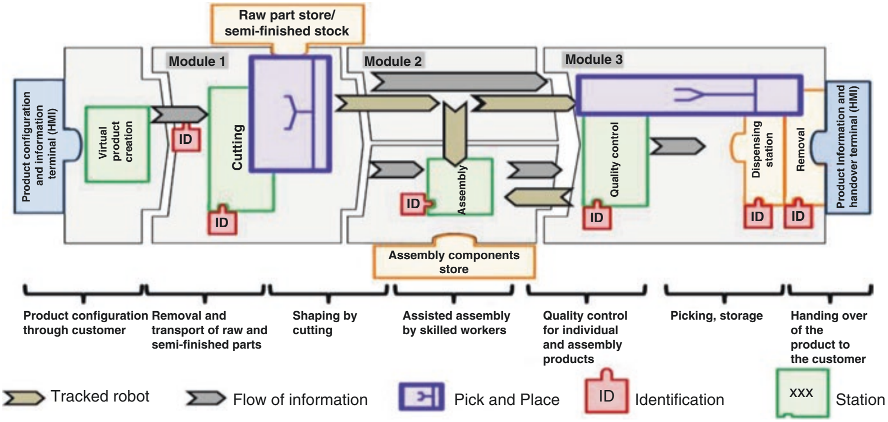

Fig. 11.3 Schematic structure of the demonstrator cell "SmartFactory 4.0"

motion and temperature sensors. It can store information about its own manufacturing. In addition, the beverage coaster receives network and Internet access and can thus trigger different services depending on the user behaviour [16].

The communication for the exchange of process and planning data takes place temporarily on the basis of software interfaces such as OPC-DA; later also OPC-UA, using WLAN, RFID and Ethernet; EtherCAT; as well as other industrial systems such as Profibus or PROFINET. The demonstrator cell also serves as a test environment for new protocols of the Internet of Things, in particular the Constrained Application Protocol (CoAP) [16].

The digital twin, here in the form of a factory model, ensures a fusion of real production and digital planning and simulation tools. Changes, whether in virtual or physical space, are bidirectionally synchronized between the demo cell and the digital twin. Autonomous processes within the demo cell can be safeguarded in advance and remain comprehensible for the human. The digital twin generates information and knowledge that are forwarded in the loop to the machines themselves, their operators, their users and to the product development [16].

11.4 Implementation of the Energy Metering System

The energy metering system consists of conversion boxes for the purpose of evaluating and monitoring the energy consumption of each component of the demonstration cell. These boxes represent the points of measuring within the beverage coaster production. Each box is composed of Euro-housing, three cable bushings with different diameters, extension cord (three-core cable) and a split-core current transformer with a ferrite core.

A split-core CT, especially one that has a ferrite core (such as the used one), can be clamped to the cable if the housing is specifically designed to do so and without using any sort of packing material, because the brittle nature of the ferrite core means that it might easily be broken, thus destroying the CT [17].

The Euro-housing is drilled in order to produce boreholes for leading the power cord through. Furthermore, the cable coating is removed, and the non-invasive current sensor is clamped around one of the three cable cores by using five windings for increasing the measuring precision.

The current measuring is done by acting as an inductor and responding to the magnetic field around a current-carrying conductor. By reading the amount of current being produced by the coil, the current passing through the conductor can be calculated. A fieldbus coupler is needed in order to measure the secondary coil voltage, which is the output voltage, and to convert the measured voltage into current in a further step. The fieldbus coupler is also used to convert the analogue input cards to EtherCAT via Ethernet cable and is connected proprietarily to the measuring cards. The operating voltage of the measuring cards and the bus coupler is 24 V/DC.

To ensure that the connected current sensor functions correctly, a power measurement of monitor, soldering station, microwave and kettle was checked. Firstly, the voltage at the sensor was measured by means of a multimeter. Furthermore, based on the measured voltage of the devices, the power at the current sensor can be determined by a conversion. To specify the measurement accuracy of the current sensor (SCT-030), the power is measured directly at the device by the help of a measuring instrument (Solalight PM-22).

Based on the comparison between the calculated power at the CT and the measured power with PM-22, the corresponding percentage error of the CT and PM-22 is between 2.4% and 13.2%.

Table 11.1 gives an overview of the various box positions. A total of eight points of measurement has been established. The measured objects can be seen in the following table.

11.5 Testbed and Research Design

Considering empty beverage coasters as raw material, it can be distinguished between green and orange coasters, whereby only their depth and gravures are different.

Table 11.1 Points of measurement

Conversion boxes no.	Measured object
1	Portal milling (*X*, *Y*, *Z*)
2	IT (computer, monitors and webcam)
3	Vacuum cleaner
4	Milling spindle
5	Robot 1 (*X* axis)
6	Robot 1 (*Y* axis)
7	Robot 1 (*Z* axis)
8	Gripper

Table 11.2 Logo and colour specifications

Coaster gravures	Specifications		
	Word logo	Colours	Picture logo
1	Friedrich	Green	Yes
2	Friedrich	Orange	Yes
3	Friedrich	Green	No
4	Friedrich	Orange	No
5	IPK	Green	Yes
6	IPK	Orange	Yes
7	IPK	Green	No
8	IPK	Orange	No

The idea behind using two different coasters with various gravures, colours and depth is to find out if the energy consumption is going to vary under otherwise similar production conditions. Therefore, eight beverage coasters have been produced in total with different gravures.

Table 11.2 shows the various specifications of the beverage coaster production. The produced beverage coasters have a defined logo that either consists of a word/picture logo or only a word logo. Moreover, the beverage coasters are produced in two different colours.

After entering the intended configuration data in the associated interface and according to the desired engraving and coaster type, the production of the beverage coaster begins. The energy process values are detected by means of the corresponding sensors at the defined eight points of measurement.

11.6 Discussion of Results

The impact of this analysis is to provide suggestions for scaling the energy metering system to larger production systems and to utilize the digital factory twin for the improvement of energy efficiency and sustainability of production systems.

Table 11.3 shows the percentage contribution per energy consumed at the eight points of measuring to the total energy consumption. The gravures on the produced beverage coasters are divided into four groups. These four types of gravures can be seen in the first column “Beverage coaster”. The last six columns are assigned to the types of energy consumption.

From Table 11.3 it can be clearly seen that the energy consumption varies from coaster to coaster, although the engravings on the beverage coasters are the same and only the type of the coaster is different.

The table shows the types of energy consumption that are required for the different production processes in the specified measuring points.

The energy consumed for realizing the gripping and milling processes as well as for the robot movement constitutes less than the energy consumption of IT devices

Table 11.3 The percentage contribution per energy consumed at the eight points of measuring to the total energy consumption (values have been rounded)

	E_{suction}		E_{IT}		$E_{\text{robot\_3\_axes}}$		$E_{\text{milling_}}$spindle		$E_{\text{cutter_3_}}$axes		E_{gripper}		E_{total}
Beverage coasters	Wh	%	Wh	%	Wh	%	Wh	%	Wh	%	Wh	%	Wh
1	146	66	33	15	22	10	9	4	4	2	4	2	220
2	145	66	33	15	22	10	9	4	4	2	4	2	219
3	110	61	27	18	18	12	7	4	3	2	3	2	170
4	109	62	28	17	17	12	7	4	3	2	3	2	169
5	61	64	18	16	12	10	4	4	2	2	2	2	100
6	61	64	16	16	12	10	4	4	2	2	2	2	99
7	24	51	10	22	7	16	2	5	1	2	1	3	46
8	23	51	10	22	7	16	2	5	1	2	1	3	46

and for the suction process. The IT energy consumption contributes nearly a quarter of the total energy consumption, which is not negligible. From the table above, it can be seen that the suction energy has the largest proportion of the total energy consumption. Furthermore, the suction process for the production of the beverage coaster is representing more than half of the total energy consumption, which means that this process consumes more energy than all the other processes combined.

A problem at the suction plate, where the beverage coasters are milled and the resulting milling shavings sucked simultaneously, can be ruled out since the energy consumption during the cutting process is not high and contributes less than 7% of the total energy consumption. This would not occur in case of malfunction of the suction plate, mainly because the engravings were milled as desired. Thus, the high energy consumption during the suction process can be explained by the fact that the vacuum cleaner consumes a lot of energy.

As the suction process consumed large amounts of energy, the process sequence is examined in more detail. It may well be that the vacuum cleaner, which is responsible for sucking the milling shavings, is malfunctioning or it is not energy efficient.

11.7 Procedure for the Implementation of an Energy Metering System

In order to find the optimal setup, the specified production system has to be divided into modules. The number of the modules depends on the production system itself. For instance, the demonstrator cell "SmartFactory 4.0" has three modules, which are destined for cutting, assembly and quality check. Once the modules have been established, the communication scheme for the data capturing, displaying, tagging and recording and the physical infrastructure of the energy metering system can be built. Energy measuring sensor and data acquisition system for energy measuring system must be designed in front of the setup of the energy metering system.

Table 11.4 Procedure for implementing an energy metering system

Step	Task
1	Set up production system
2	Divide system into modules
3	Choose points of measurement
4	Set up energy measurement system
5	Test runs and analysis
6	Identify improvement measures
7	Development of simulation model
8	Continuous improvement of the model with measured data and improvement of energy efficiency

As the energy measuring is carried out at measuring points in order to control and monitor the energy consumption in different subprocesses, it is important to choose a useful position of the measuring points for a clear overview of the consumptions throughout the production. After choosing the points, the energy metering system can be entirely implemented.

For controlling the production system, test runs can be started. The test results can be analysed in a further step.

To make the production processes more efficient, continuous improvement measures have to be identified. The development of a simulation model can make the identification of improvement possibilities easier if this simulation model enables the calculation of the energy consumption before the production with changing parameters and for various production scenarios. This will help the customer to select the most efficient variant. The continuous improvement of the model can be realized with the measured data during the production processes, and thus the improvement of the energy efficiency of the production system can be reached.

Table 11.4 summarizes the necessary steps in order to implement an energy metering system.

11.8 Conclusion

In this paper, the production system “SmartFactory 4.0” and the associated energy metering system have been presented and explained. The analysis of the resulting data during the production of the beverage coasters highlighted that there is room for process improvement.

The proposed energy metering system helps making a leap towards complying the high requirements relating to Industry 4.0. For reaching an energy-efficient production in the context of smart production, the use of energy-efficient system elements and modules can be helpful to improve the energy consumption during the entire production. In addition to measuring the energy consumption during the production, the aforementioned simulation model should be included in the future energy metering system.

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Chapter 12
Quality Assessment of Plastic Recyclates from Waste Electrical and Electronic Equipment (WEEE): A Case Study for Desktop Computers, Laptops, and Tablets

Florian Wagner, Jef Peeters, Jozefien De Keyzer, Joost Duflou, and Wim Dewulf

Abbreviations

ABS	Acrylonitrile butadiene styrene terpolymer
FTIR	Fourier transform infrared
GC-MS	Gas chromatography-mass spectrometry
HIPS	High-impact polystyrene
MFI	Melt flow index
PC	Polycarbonate
PMMA	Polymethyl methacrylate
WEEE	Waste electrical and electronic equipment

12.1 Introduction

Waste electronic and electrical equipment (WEEE) consist of a large variety of products with different plastics. It is important to assess the changes of these waste streams in order for recycling companies to be able to adapt their processes. For the end-of-life treatment, the plastic composition found in these waste streams is a crucial aspect in order to

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evaluate the value of a waste stream. However, only information on the plastic composition will not give an estimation on the final quality of the plastics recyclates that can be produced with a specific input composition. For example, the efficiency of the liberation and separation in the recycling process will strongly influence the final purity and, accordingly, the quality. In addition, the design of the waste products, as well as the condition of the plastics applied in these products, can make an impact. Therefore, the quality of the recycled plastic will depend both on the product input and on the recycling process.

In the ISO 8402, quality is defined as follows: "the totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs." This definition is interpreted in different ways by different stakeholders or actors in the value chain, as it is not fully measurable due to different perceptions of satisfaction and implied needs. David Garvin [1] categorized quality, depending on the perspective, into transcendent-based, product-based, used-based, manufacturing-based, and value-based quality. The transcendent-based view is characterized by a subjective relationship to the product or service, where emotions like pleasure or fun are included, which can be reflected by the phrase "I can't define it, but I know it when I see it" [2]. The product-based view sees quality as a measureable characteristic that is set by benchmarks. Depending on the characteristics included in the evaluation, these can be more objective or subjective. In the used-based view, quality is seen as an individual matter, where only the user can judge whether his requirements were met or not, and the manufacturing-based view defines quality as a conformance to requirements that are defined by the manufacturer [1–3]. None of these approaches claim to include the total quality, which could only be considered when met with all approaches. In plastics, recycling quality is a very present issue as it decides whether a recycled plastic is purchased and used by an equipment manufacturer, as well as the price at which the material is sold. Quality in plastic recycling is mostly reflected by the requirement to achieve properties close to, or even better than, virgin plastics. These requirements are set by the equipment manufacturers in the form of technical requirements or by governments or the European Union in the form of thresholds to avoid the presence of certain substances. Recyclers are on the one hand confronted with the challenge to reach these requirements and on the other hand to maintain them. This is particularly challenging due to the long chain of different recycling processes which all influence the final quality of the produced recyclates, such as depollution, liberation, separation, washing, drying, etc. Another commonly faced challenge is that it is not possible to evaluate whether quality flaws originate from the process or the input material. For this reason, Vilaplana et al. developed key parameters to assess the quality of recycled plastics [4, 5]. However, this concept is focused on the analysis of the obtained plastic recyclates and does not consider the evaluation of the quality of a mixed waste input. In addition, the interrelated influences of both product and recycling process properties on the final quality of the plastic recyclates are not considered in prior developed methods. In consequence, little insights of the origin of possible quality flaws are given, and only incremental improvements of the quality are possible, not providing the opportunity for radical innovations.

Therefore, a scheme for the assessment of the quality of plastic recyclates and mixed plastic waste streams is presented in this paper. Relationships between properties of the input, the recycling process, and the resulting final quality of plastic recyclates can be identified in order to produce high-quality plastic recyclates.

12.2 Materials

12.2.1 Case Study: Desktop Computer Housings, Laptop Back Covers, and Tablet Housings

In this research desktop computer housings, laptop back covers, and tablet housings have been selected as a case study as they can be treated by a disassembly-based recycling process. The process is described by Wagner et al. [6] and is composed of disassembly steps of the targeted components and further purification in a density separation step after shredding in order to remove melt inserts, printed wiring board parts, and other impurities that result due to the design of the components. The identification of the plastic types present in the housing components is done by FTIR specytrometry.

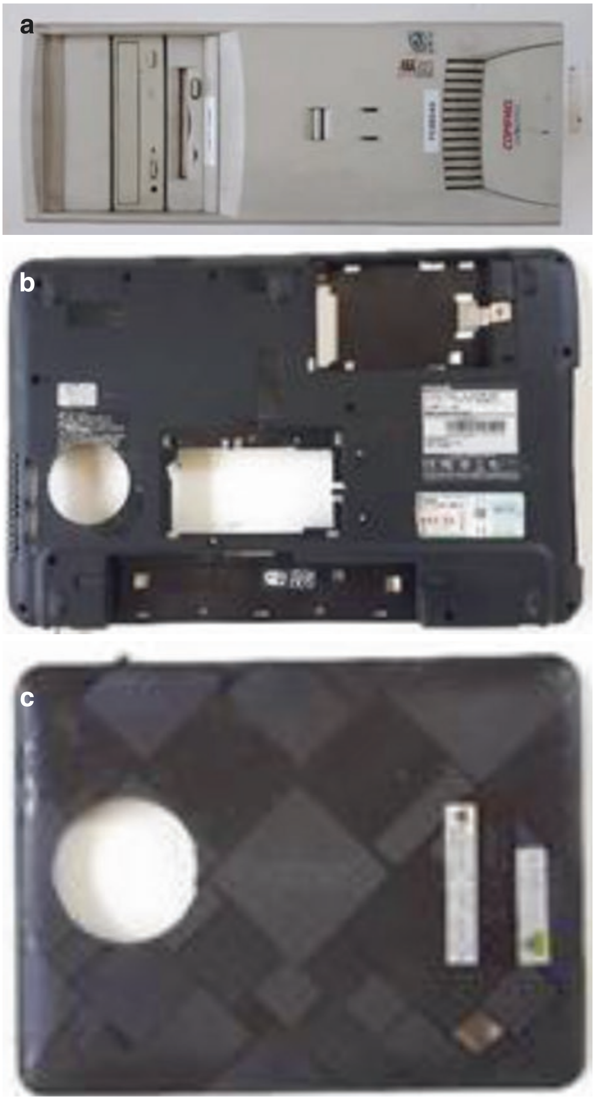
12.2.2 Sampling

The sampling was carried out at a recycling facility in Belgium in 2016. In total, 81 front covers from desktop computer housings, 166 laptop back covers, and 73 tablet housings from postconsumer waste were disassembled, and examples of the components are shown in Fig. 12.1. The in-molded production year was recorded for every component, and discs with approximately 5 cm diameter were drilled out of the housings to determine the plastic type in the lab.

12.2.3 Fourier Transform Infrared (FTIR) Spectroscopy

In this research Fourier transform infrared (FTIR) spectroscopy is used to determine the plastic type of the different housing materials. The equipment used was a Perkin Elmer 100 FTIR, and the measuring technique used was attenuated total reflectance (ATR). Small pieces were cut from the sampling discs in order to get a good contact between the plastic and the crystal. The samples were measured with 4 cm^{-1} resolution, and an average of 16 scans was used for every spectrum. The identification was carried out by the comparison to the spectra of a database, based on previous measurements. For the chemical aging content, the carbonyl and trans-1,4-polybutadiene peaks at 1750 and 966 cm^{-1} were analyzed, respectively. From the functional group indexes, fractions were formed with the areas of these peaks and the area of a stable peak at 1600 cm^{-1} [5]. FTIR spectroscopy is a analysis technique that is commonly used in polymer analysis labs as well as for quality management in industrial applications. Therefore, it was chosen as for the disassembly-based recycling process in order to evaluate the potential quality of the waste stream.

Fig. 12.1 Examples of desktop computer housing (**a**), laptop back cover (**b**), and tablet housing (**c**)



12.3 Methods

12.3.1 Quality of Plastics from Waste Electrical and Electronic Equipment

The objective of the proposed scheme is to define the highest final quality of a plastic recyclate that can be achieved with mechanical recycling (potential quality) when a specific input of a waste stream or waste product is provided. This potential quality can be recovered by the recycling process. The final quality of the recycled plastic is the result of the potential input quality and the recovery efficiency of the recycling process.

In the theory of a virgin plastic, which was designed for a certain application, does not suffer any physical or chemical aging during its lifetime, and is recovered with a 100% purity, it will possess the same relative quality after recycling. A loss in quality will occur if any loss in properties of the plastic takes place. This can be due to the loss of any physical or chemical properties, such as mechanical values, rheological properties, and aesthetical properties, as well as due to the loss of any functionality such as flammability or UV resistance. This loss in quality of the recycled plastic is proposed to originate from either the purity (amount of foreign bodies in the plastic) or the condition of the plastic (aging of the plastic). The resulting loss in quality of these two parameters will depend on the effect they have on the properties that are defined as quality measures. The scheme gives an overview of the factors that can result in property losses or property variations of recycled plastics. The factors are displayed in Fig. 12.2 as boxes

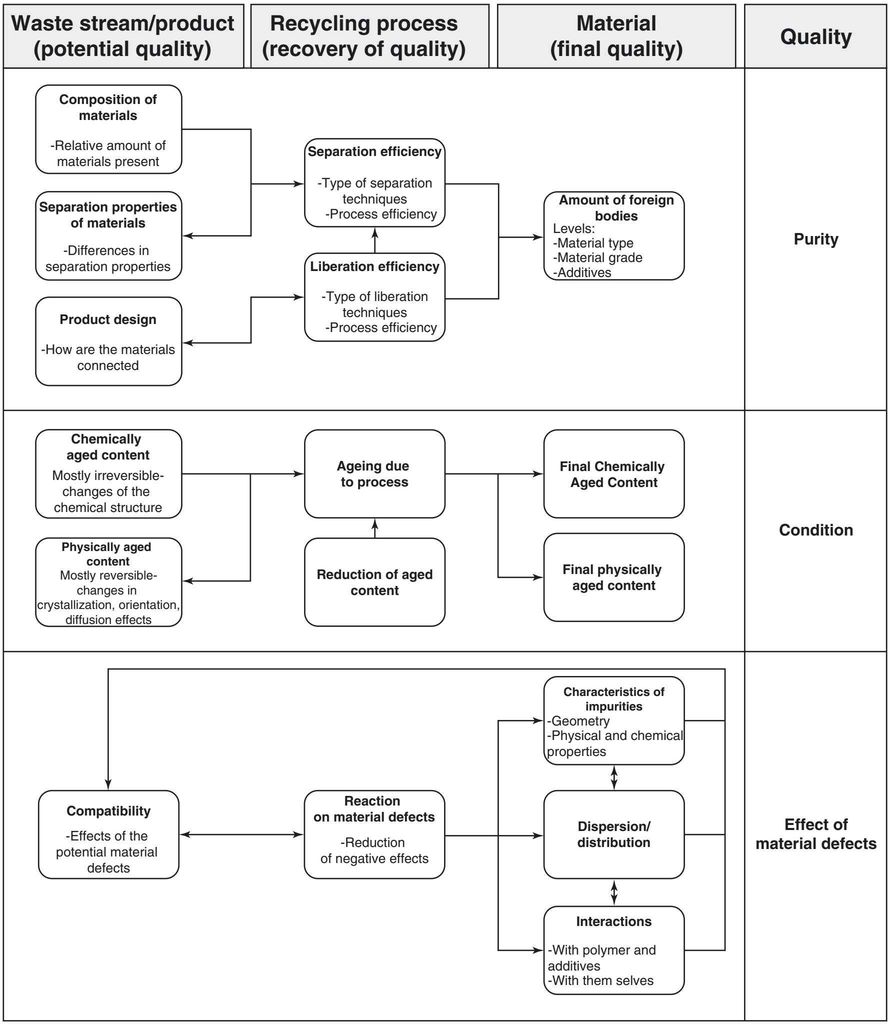


Fig. 12.2 Scheme for the assessment of the quality of plastic recyclates and mixed plastic waste streams for mechanical recycling

with arrows indicating the influences in between them. The factors are categorized in three stages, the waste stream or waste product (input), the recycling process, and the final recycled plastic (output). The specific measures on what aspects are relevant to quantify the quality (mechanical values, aesthetics, consumer perception, etc.) for the proposed scheme will depend on the applied case study and are not defined in this paper. The key parameters that define the quality, the purity, and the condition of the plastic and the effects of these material defects are explained in the following sections in more detail.

12.3.1.1 Purity

Purity is defined by the presence or absence of foreign bodies in the polymer matrix. A 100% pure plastic will contain no impurities such as metals, label pieces, or other plastics that could cause a loss in properties of the recycled plastic. However, it needs to be defined what is considered an impurity (or foreign body). This scheme proposes three levels of purity: the material type, the material grade, and the additives. Based on the example of ABS, at the material level, all different kinds of ABS could be mixed, and the final recyclate could be considered pure if no other plastic is contained in its matrix. The material grade level also considers that there is a variety of ABS grades on the market with very different properties, and ABS would be considered pure if, for instance, only high-impact grades are contained in the final recyclate as a dilution of high-impact grades in low-impact grades would result in a loss in impact strength of the final recyclate compared to the impact strength of the plastic before recycling. At the additive level, also flame-retardant ABS or ABS with high UV resistance would be considered.

The amount of foreign bodies in the recycled plastic (material) defines the purity and is a result of both the waste stream/products and the recycling process. Factors that influence the purity of the waste stream or waste product are the composition of materials, the separation properties of the materials, and the product design. These factors define the potential purity that can result from a given waste stream and therefore contribute to the potential quality of the waste stream or waste product. In the scheme in Fig. 12.2, the influences between different factors are shown as connections with arrows, where the direction of the arrow shows indicates if a factor only influences or is also influenced by another factor. The composition of materials can be analyzed to know the relative share of materials present in a waste stream or waste product. The composition will also give an indication of a potential purity so that for a waste stream that consists of 90% of one specific material, a high purity after recovery can be assumed, as only little potential impurities are present. The second factor that will influence the potential purity of a waste product is the separation properties of the materials, and this factor strongly depends on the subsequent recycling process, as indicated by the back-going arrow in Fig. 12.2. The applied separation techniques will define the properties the materials are separated by, for instance, the density, surface wettability, electrostatic properties, or responses to spectroscopic techniques. The factor product design includes how the materials in the waste product are joined together as a separation in materials can only take place if the materials are liberated. WEEE products are joined with different techniques, and the type and amount of fasteners may influence the purity depending on the applied liberation technique. The function of the recycling process is the recovery of the potential waste stream or waste product, and the purity is influenced by two factors, the separation efficiency and the liberation efficiency. The separation efficiency of different materials in a recycling process is defined by the separation techniques and depends both on the efficiency of these techniques and on the input materials (differences in materials), as indicated by the double arrow in the Scheme. A density-based separation process, for instance, will result in a higher purity if the densities of the materials are significantly different and do not show any overlaps. Another factor that will influence the separation efficiency is the liberation efficiency of the recycling process itself, as unliberated materials cannot be separated. This liberation efficiency depends on the applied technique, such as shredding or dismantling, as well as on the product design of the waste product, for instance, the type and amount of different connections between the materials. These five factors of the waste stream or product and the recycling process will influence the amount of foreign bodies in the recycled material and define its final purity.

12.3.1.2 Condition

The condition of the plastic is determined by the degree of aging, which is defined as the chemical and physical changes that occur in the plastics during their lifetime and processing. As shown in the scheme, the condition for waste streams or products is defined in two factors, the chemically aged content and the physically aged content. Chemical aging includes essentially the change of the molecular structure of the polymer chain or additives, such as molar mass changes, cross-linking or degradation, the formation of functional groups, or the formation of low-molecular products. Physical aging includes changes in crystallization behavior and orientations, decrease in internal tensions, and relaxation processes but also the diffusion of additives or external low-molecular products in and outside of the plastic matrix [7]. Which aging processes occur in the plastic strongly depends on environmental conditions such as moisture, oxygen concentration, temperature, or electromagnetic irradiation, but also processing conditions such as temperature or shear rates can cause the plastic to age [7–10]. The aged content is a condition of the material that reduces the potential quality of the waste stream or product as it can affect the properties of the final recyclate. The condition of the materials in the waste stream or product does not depend on the subsequent recycling process. This is shown in the scheme the arrows go from the waste stream or waste product to the recycling process and then further to the final recycled material. In the recycling process, the condition the additional aging of the plastic can occur, such as chain scission in the shredding process, oxidation and further degradation during the compounding, or additional moisture due to the washing. Chemical aging processes are mostly irreversible and are therefore crucial to analyze regarding the recycling of plastics as they can significantly deteriorate the mechanical or aesthetical properties and affect the long-term stability of the plastic [7–10]. Most physical aging processes, except the loss of additives, will naturally be reversed during the compounding step of the recycling process. For the physical aging due to the diffusion of low-molecular products or moisture, special processing steps such as degassing during compounding can be taken to reduce their content. It is also possible to react on some of the aging processes that are considered irreversible, such as the loss of additives, reduced rubber content due to cross-linking, or also chain scission. As this requires the addition of new chemicals, it is seen as a reaction or buffering of quality losses rather than the recovery of potential quality and is therefore not included in this scheme.

12.3.1.3 Effects of Material Defects

The presence of foreign bodies or degraded content in the polymer is summarized as material defects, which may have an effect on different properties of the material. This key parameter is the most complex one to assess as it aims to predict the correlations between the defects and the final quality. As shown in the scheme, the factors that influence the effect of the defects are strongly interconnected and therefore difficult to assess. For the evaluation of the waste stream or waste product based on the compatibility of the materials that are present, significant knowledge of the final recycled material is necessary. This is contrary to the key factors purity and condition where knowledge of the input and process are necessary in order to estimate and explain final quality losses. On the level of the recycled material in the scheme, the extent to which the defects decrease the quality depends on the characteristics of the impurities, the dispersion and distribution, and the interactions that take place. The characteristics of the impurity, such as size and shape, can change the effect the impurities have on the properties [11]. For instance, it is known that the mechanical properties of plastics improve when the reinforcement in the polymer matrix is done by glass beads or by glass fibers. In addition, physical characteristics of the foreign bodies such as hardness, stiffness, ductility, etc., will influence the mechanical behavior of the foreign body in the polymer matrix. The chemical properties of material defects, such as functional groups that form due to the oxidation of the polymer, can influence the long-term aging behavior of the plastic [7]. Furthermore, the distribution as well as the dispersion of the impurities in the polymer matrix can influence the way the impurities affect the overall behavior of the polymer. Finally, the interactions between the impurities and between the impurities and the plastic and its additives can play a crucial role and strongly influence the quality. These three factors will be largely determined by the recycling process that influences the size of the final impurities and their dispersion/distribution and might also affect their interactions based on processing conditions. If occurring in a controlled manner, this influence of the recycling process can also determine the compatibility of the materials in the waste stream or product as indicated by the double arrow. Interactions of impurities can be influenced by the addition of, for example, compatibilizers, so that the effect of the impurities can be reduced or the impurities can even improve the plastic quality as shown by Ragaert et al. [12, 13]. Hence, the evaluation of the effect of the material defects strongly depends on which impurities and defects are found in the recycled plastic and the reactions that can be taken in the applied recycling process.

12.4 Results

The proposed scheme to assess the quality in plastic recycling was applied on the case study of desktop computer housings, laptop back covers, and tablet housings to evaluate the potential quality of the waste stream regarding a disassembly-based recycling strategy. The six factors composition of materials, separation properties of materials, product design, chemically aged content, physically aged content, and compatibility that influence the potential quality are discussed.

12.4.1 Composition of Materials

The analysis of the different materials applied in the plastic components shows that desktop computer housings are composed of 57% acrylonitrile butadiene styrene (ABS) terpolymer, 30% metal, and 14% polycarbonate/ABS (PC/ABS) blend. The laptop back covers are strongly dominated by PC/ABS (92%), 3% ABS, 2% ABS/polymethyl methacrylate (ABS/PMMA) blend, as well as 2% metal. The tablet housings show the largest amount of different materials applied with 42% ABS, 30% metal, 11% PC/ABS, 8% ABS/PMMA, and 8% high-impact polystyrene (HIPS). The compositions of the analyzed components are shown as percentages in Fig. 12.3. Quantities of measured samples are displayed as numbers directly in the columns. ABS and HIPS are commercially recycled on an industrial scale, while ABS/PMMA cannot be found as a separate material on the recyclate market. In recent time increasing interest has been dedicated to the recycling of PC/ABS, as it is a very promising material due to its good properties. It is only recycled by a limited number of recyclers, and laptop back covers could be a promising source for the recovery as it is a relatively pure waste stream with only 7% of other housing materials. Based on these compositions, it can be assumed that the PC/ABS from laptop back covers can be recycled with a high purity as only mior amounts of ABS and ABS/PMMA could become impurities due to sorting mistakes. The desktop computer housings and tablet housings show a more mixed composition and therefore a higher risk of impurities. The flame-retardant (FR) content in ABS and HIPS is not considered in this study and could result in a significant change in quality as many brominated FRs are banned by bodies of the European Union.

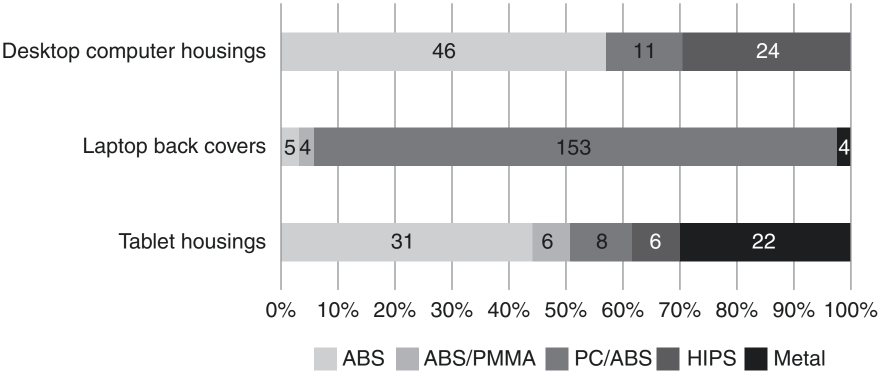


Fig. 12.3 Material composition of desktop computer housings, laptop back covers, and tablet housings based on the analysis of 320 housings in 2016

Table 12.1 Visualization of IR-active differences due to the chemical composition of the plastics HIPS, ABS, PC/ABS, and ABS/PMMA

Chemical composition	PS	PB	A	PC	PMMA
HIPS	✓	✓			
ABS	✓	✓	✓		
PC/ABS	✓	✓	✓	✓	
ABS/PMMA	✓	✓	✓		✓

12.4.2 Separation Properties of Materials

Table 12.1 shows differences in the separation properties of the plastics present in the analysed waste streams, where FTIR spectroscopy is used as a sparation technique. The differences in IR responses are visualized based on the chemical composition of the plastics HIPS, ABS, PC/ABS, and ABS/PMMA. The separation properties of the plastics in the waste stream are discussed based on a separation with FTIR spectrometry and subsequent sorting, as this technology is available as robust equipment and is suitable for the disassembly-based recycling process. The plastics HIPS, ABS, PC/ABS, and ABS/PMMA can be identified based on their chemical structure. The plastics can be distinguished due to the presence or absence of IR-active groups based on their chemical composition as visualized in Table 12.1. The chemical composition of the discussed plastics is the result of different monomer contents in the polymer chain that can be identified by FTIR. PS represents the polystyrene content that is characterized by the main IR peaks at the wave numbers 3000–3100, 2000–1600, 1600, 760, and 906 cm^{-1}. A polybutadiene (PB) content is measureable at 1640, 965, and 910 cm^{-1}, and the acrylonitrile (A) content results in a peak at 2240 cm^{-1}. The typical peaks of a polycarbonate (PC) content in the polymer chain are mainly visible at 1785, 1250, and 860 cm^{-1}, and the polymethyl methacrylate (PMMA) content can be observed at 1470–1370, 1260, 1170, 1200, and 835 cm^{-1} [14, 15].

12.4.3 Product Design

The desktop computer housings, laptop back covers, and tablet housings consist mostly of one large plastic piece. The components are characterized by different joining techniques such as screws or snap connections that influence the liberation due to the disassembly process of the recycling technique but should not influence the final purity. However, remaining metal inserts, printed wiring board parts, or cables can be connected to the plastic components, and labels are often glued to the outside of the product. These impurities can be largely removed by a density separation step of the regarded process, but especially labels have been shown to still remain in the recycled plastic and therefore reduce the final quality of the recycled plastics [6].

12.4.4 Chemically Aged Content

The chemically aged content is discussed based on the FTIR spectra from ABS from desktop computer housings. ABS was selected as it makes up the largest material share of desktop computer housings and tablet housings, and oxidation reactions of the polymer are clearly visible in the FTIR spectra. The functional group indexes of the carbonyl and trans-1,4-polybutadiene content from the FTIR spectra of ABS desktop computer housings with different production years are displayed with standard variations in Fig. 12.4. Previous studies show that oxidation of ABS and a decrease of the polybutadiene content are significant chemical aging processes that

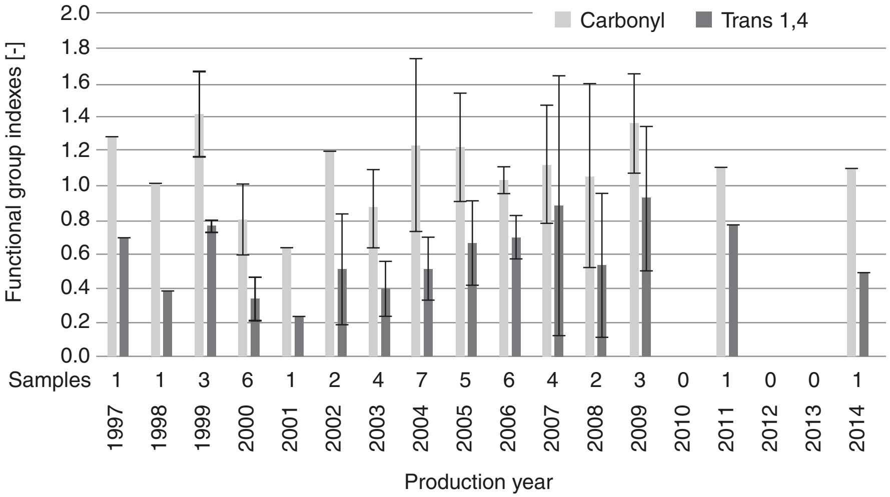


Fig. 12.4 Functional group indexes of carbonyl and trans-1m,4-polybutadiene content of postconsumer ABS from desktop computer housings with different production years

may occur in this material that can strongly affect the mechanical properties [16, 17]. The ABS samples clearly show the presence of carbonyl groups, which are most likely the result of an oxidation of the polymer chain. However, no correlation can be observed regarding the year of production of the ABS components and the level of oxidation. Also no decrease in the trans-1,4-polybutadiene content can be observed with regard to the production year. This is due to the fact that polymer degradation is favored by environmental conditions such as temperature and electromagnetic irradiation. The environment the components were exposed to will affect the aging more than their age [7]. The FTIR measurements only measure the surface of the plastic so that the observed oxidation and polybutadiene contents may not represent the entire plastic component. In most cases the aging on the surface will be more severe than inside the component due to higher levels of oxygen, electromagnetic irradiation, and moisture [7].

PC/ABS does show a peak at around 1785 cm^{-1} due to its molecular structure [14] which can overlap oxidation peaks of carbonyl groups formed due to oxidation that also show peaks in this wave number range. A differentiation between these carbonyl contents would require more sophisticated methods and was therefore not done in this study. As the ABS phase in PC/ABS is more sensitive to degradation, a similar chemically aged content as for ABS is assumed.

FTIR also has some disadvantages. The scission of the polymer chain is not visible, if not accompanied by the formation of visible groups; also only the trans-1,4-polybutadiene content can be measured, whereas the cis-1,4 structure of polybutadiene only shows a weak response in FTIR. Therefore additional analysis is necessary. The cis-1,4-polybutadiene structure could be detected with Raman spectroscopy, and also chain scission could be indicated by rheological measurements such as the melt flow index (MFI), which is a fast standard test applied in industry. For the ABS a good quality can be assumed as no severe degradation can be seen [18]. Detailed effects of the observed degradation would need to be investigated, but based on the FTIR analysis in this research, no severe losses in impact properties of the final recyclates need to be assumed, which is one of the main quality measures for the investigated materials as degradation will usually first affect the polybutadiene content. However, the presence of oxidation of the polymer chain might influence the final quality as Boldizar and Moeller have shown that a decrease in properties of reprocessed plastic can be more pronounced depending on the aged content [19].

12.4.5 Physically Aged Content

Additionally, all samples showed peaks with different intensities in the area of 3000–3500 cm^{-1}. These peaks are most likely caused by OH groups present in the polymer. In the case of ABS, this is likely due to moisture or oxidation. Due to the fact that there is carbonyl group formation in the polymer, it is also likely that part of the OH peak is due to the formation of functional OH groups in the polymer surface caused by oxidation. However, ABS is a hydrophilic polymer that requires pre-drying before processing due to moisture absorption in the polymer during storage. It is very likely that moisture makes up an extensive contribution to the OH peaks of the materials. Moisture in the polymer surface is considered a reversible physical aging content as it can be removed due to drying, during or after the recycling process, in a drying step, or during the degassing in compounding. An additional drying step before the FTIR measurement for the assessment of the plastic quality for recycling should also be considered as it would also allow to assess possible oxidation content in PC/ABS. The presence of moisture in the polymer does not necessarily result in a decrease in quality of the polymer as it may be removed in a drying step. However, moisture may favor degradation processes during the processing and can result in splay marks on the final injection-molded product.

Low-molecular-weight impurities can result from chemical degradation processes or contamination from external sources and might be visible in FTIR if present in sufficiently large concentrations. For the proposed waste products, no major contaminations could be observed by FTIR and are not expected. However, to fully exclude the risk of contamination with low-molecular substances, chemical analysis techniques such as gas chromatography with mass spectrometry (GC-MS) as proposed by Vilaplana et al. [5] would be required.

12.4.6 Compatibility

According to Peeters et al. [20] and Brennan et al. [21], ABS and HIPS show a reasonable miscibility with decreasing mechanical properties when being mixed. The miscibility of PC and PMMA has been broadly studied by different researches [22–24] and depends on the preparation method; as without modification and correct mixing conditions, the polymers are not compatible. Rybnicek et al. [25] investigated the blending of PC/ABS/PMMA and showed that good properties are possible depending on the ratios of the materials, as the SAN phase in ABS takes the role of a compatibilizer. A low content of impurities of one of the recycled materials should therefore not affect the quality significantly. However, metals from inserts and screws could result in a decrease in the final quality if not separated properly. The laptop back covers can therefore show a high potential quality, as the possible minor impurities of ABS and ABS/PMMA in the largely PC/ABS-dominated waste stream also show a good compatibility. The mixed waste streams of desktop computer and tablet housings show a lower potential quality as there are relatively large shares of both ABS and HIPS present that could cause a decrease in the final properties of the recycled plastic.

12.5 Summary and Conclusion

A scheme to assess the quality of waste plastics is proposed and applied on a case study of desktop computer housings, laptops, and tablet housings. For the evaluation of a waste stream or waste product, the proposed scheme shows that the chemically and the physically aged content can be seen as an input condition that does not depend on the applied recycling process. This also applies to the material composition of the waste stream. Accordingly, the evaluation of these factors can be done based on the analysis of the materials, while the evaluation of the differences in materials and the product design requires knowledge about the recycling process. Furthermore, the compatibility is also influenced by the recycling process and additionally requires knowledge about how potential material defects due to impurities or aged content may influence the final quality of the recycled plastic. This scheme is designed to evaluate the quality of waste streams and recycled plastics from mechanical recycling and does not include upcycling or upgrading of the recycled plastic. This is because in this scheme, quality is seen as a potential characteristic of the waste plastics that can be maintained if no defects in the material occur during the lifetime and the recycling process. Many upcycling and chemical recycling approaches result in significant changes of the chemical structure and in some cases completely depolymerize the plastics into monomers and then create entirely new plastics. Therefore, the principle of increasing defects and resulting losses in properties or functions of the plastics is not entirely suitable, and an adaptation of the scheme would be necessary.

Regarding the potential recovery of the components, the evaluation was done assuming a disassembly-based mechanical recycling strategy. This recycling technique is based on the disassembly of the plastic component, the identification and subsequent sorting based on FTIR technology, and final purification processes based on density separation. The waste products are composed of HIPS, ABS, PC/ABS, and ABS/PMMA, where the laptop back covers were largely dominated by PC/ABS, while the desktop computer and tablet housings showed a larger mix in applied plastics. The laptop back covers are therefore assumed to have a higher potential quality based on the waste stream composition. The separation properties of all components could be considered relatively similar if separated by FTIR technology and also if the product design did not differ significantly. Consequently, all housings show the potential to reach a relatively high final purity if processed with disassembly-based mechanical recycling. However, potential impurities, such as labels glued on the plastic components, have been found on the analyzed components and were shown to remain in the recyclate after the process. Indications for chemical and physical aging were analyzed for the ABS for desktop computer housings, and potential signs for oxidation and moisture are found that could affect the long-term stability of the plastic. Presented results demonstrated that degradation levels are independent from the production date of the plastic component. Also the polybutadiene levels indicate a good impact performance of the investigated plastics. As the oxidation levels are relatively low, no significant decrease in the final properties is assumed for these waste products. However, the observed oxidation could result in a reduced long-term stability of the recycled plastics, and potential impurities could lower the mechanical properties of the recycled plastics. In total low degradation levels and a potential high purity allow to assume a high final quality of the recycled plastics from desktop computer housings, laptop back covers, and tablet housings if processed by disassembly-based recycling process.

However, in future research, the effects of the degree of degradation and the potential impurities have on the plastic properties will need to be further investigated. Additionally, research will quantify the quality of a plastic recyclate in the function of a final application and focus on the connections between the waste input quality and output quality.

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Chapter 13

Design and Control of Remote Operation Devices for Remote Recycling

Akiho Chiba, Akihiro Oikawa, Yuta Kadowaki, and Nozomu Mishima

13.1 Introduction

Recently in Japan, recovery of precious and critical metals from used electronics, the so-called urban mines, is an emerging problem [1–3]. It is said that the amount of gold which is equivalent to 16% of proven reserves is contained in used products in Japan. And 23% of proven reserves of silver exists in the Japanese urban mines. In order to promote extraction of metals from used products, a legislation started from April, 2013. However, return rate of used products is insufficient. As a countermeasure of the situation, the authors' research group has proposed a new recycling method named remote recycling, in order to reduce the recycling cost. The method is to separate valuable parts from PCB (printed circuit board) with non-valuable parts mainly from outer case, by remote operation. Using smartphones as a case study, the paper tries to insist that the method is a promising way for replacing the conventional recycling process for intermediate treatment of used products.

In the previous study [4, 5], we have applied the method to the case study and basically proved that the remote separation technique can be applied to the recycling process of small electronics. However, in the previous system, the linear mechanism which is to approach to the target particles and the vertical motion system to generate the sorting motion were separately controlled. In addition, the preciseness of the displacement sensor was not enough. Because of these reasons, separation quality was not enough. Thus, the objective of this study is to renew the mechanism and the control system. Through the remote separation experiment using the new system, the study aims to show remote separation is precise enough to recover most of the valuable parts. In the new system, two necessary motions are synchronously controlled using microcomputer and programming language called

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Python. A new control sequence was developed so that the operator only needs to push a virtual button on the pc desktop when the particles that seem to be valuable come along the conveyor.

13.2 Concept of Remote Recycling

The objective of proposing the concept named "remote recycling" is to reduce cost of intermediate process of recycling that requires considerable labor cost. In Japan, or in every other country, establishment of circular economy through recycling of used products is an emerging problem. However, when the amounts of treated products increase and the complex recycling process recovering many types of metals has become popular, large amount of labor will be necessary. It might be difficult for current recycling industry to respond to such situation. It will be important to consider a way to ease the situation. The concept of remote recycling has these advantages, if the practical system has been implemented.

1. Operation can be carried out from overseas where labor cost is relatively low.
2. The secondary resource can be kept in the country.
3. Special knowledge for disassembly is unnecessary.
4. It is possible to respond to various products flexibly.
5. By adopting design knowledge, high-quality separation will be possible.

Although remote recycling is still in its conceptual stage, through research group's effort by now, the concept has been realized as the prototype level. Figure 13.1 shows the schematic view of the concept.

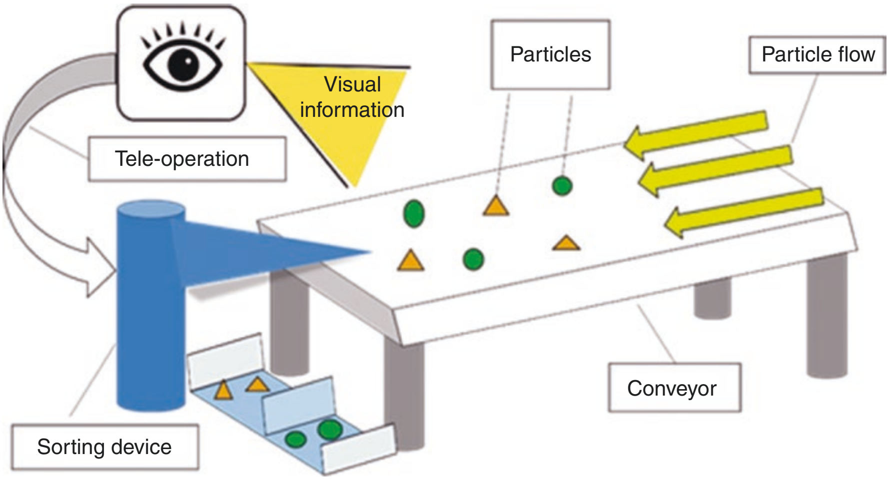

Fig. 13.1 Schematic view of the concept of "remote recycling"

13.3 Basic Procedure of Remote Recycling

13.3.1 General Procedure

Basic procedure of remote recycling starts from rough shredding of used small electronics such as mobile phones or digital cameras. Shredded particles flow on the conveyor, and then the visual information is sent to operators via Internet. The operators separate the particles watching the internet vision. Based on the operation command, the robot arm set by the conveyor moves to separate particles which seem to include valuable metals and surrounding particles. Since the operations will be carried out via Internet, time delay is one of the problems to be solved.

The abovementioned procedure is the basic process of remote recycling. But there are many other problems. It is necessary to find proper size of the particles, how to prevent sticking of particles because of electrostatic force, and so on. By studying such problems, the concept can be put into practice.

13.3.2 Design and Prototyping of the Arm

Separation mechanism is consisted of a linear actuator (Misumi corp. RS306B) and an arm to push out selected particles. The arm is controlled up and down synchronously to the linear motion by a servomotor connected to a microcomputer board called Arduino Uno. This is to push out valuable particles without touching unnecessary particles and to return to the initial position after one sequence. Time to complete one sequence is approximately 1 s (Fig. 13.2).

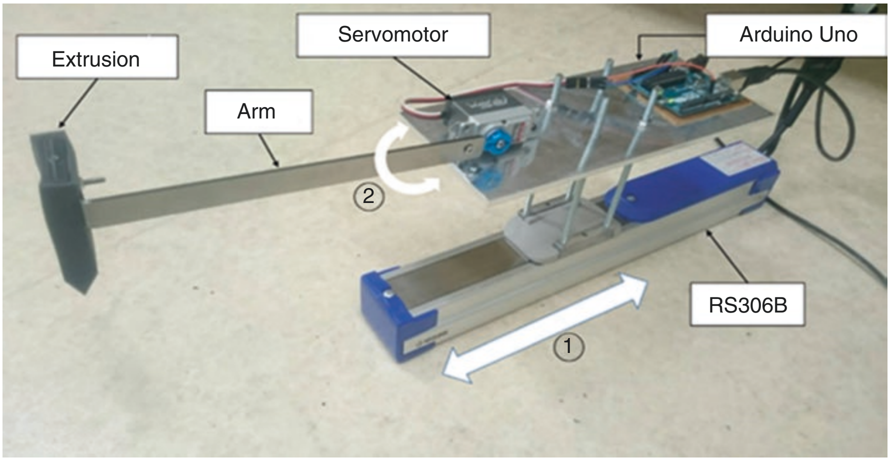

Fig. 13.2 Setup for remote recycling

13.3.3 Control System

Previous controlling of the servomotor was using the microcomputer board for controlling. Based on the sensing data of a displacement sensor, the servomotor controls the arm up and down. However, accuracy of the displacement sensor was nor so high. The lower structure was controlled by a special software. Since the two motions were controlled separately, it might happen that the arm touches the unnecessary particles. Contrarily, using the new control software, the lower structure is controlled by a developed software by Python, and the controller of the upper structure is also embedded in the software. So, the two motions can be controlled synchronously.

13.3.4 Remote Operation Setup

The computer connected to the separation arm is controlled remotely by using Chrome Remote Desktop. Display image of the remote host which is located at the operators' side is shown in Fig. 13.3.

13.3.5 Remote Controlling System

As the first step of remote separation experiment, "Chrome Remote Desktop" by Google was used, since it is easy to apply. A special software should be coded after now. However, for the purpose this time, "Remote Desktop" will have sufficient performances (Fig. 13.4).

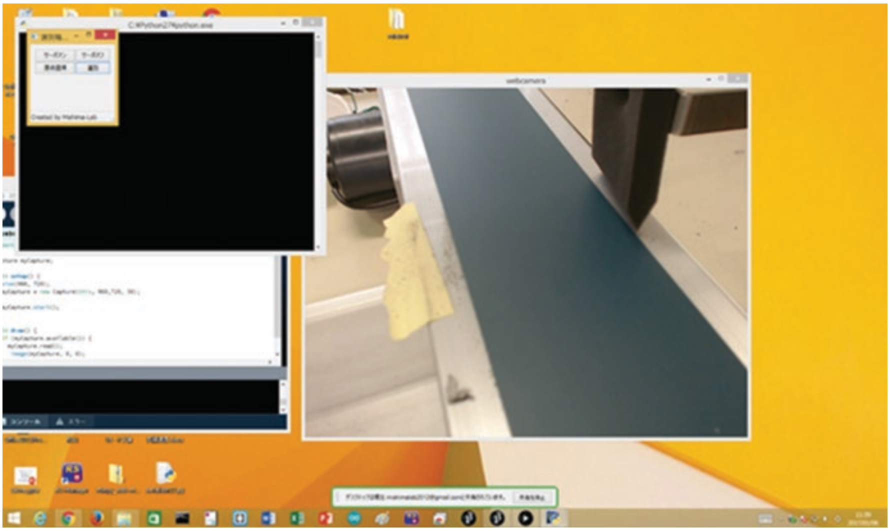

Fig. 13.3 Remote desktop showing the image

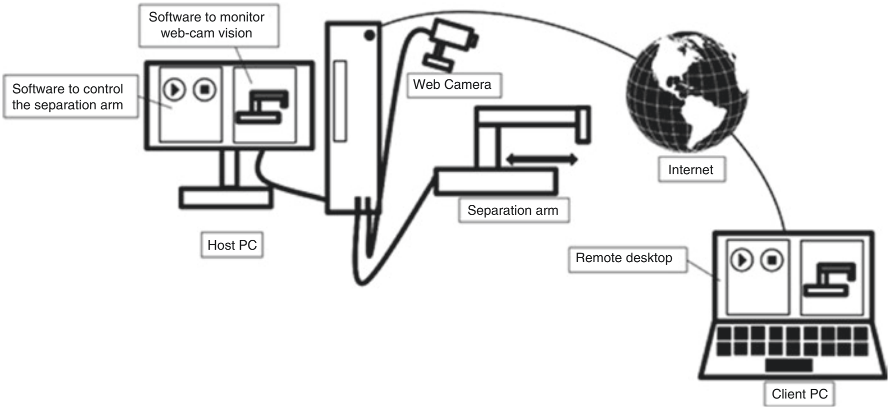

Fig. 13.4 Schematic view of the remote controlling system

The remote separation experiments are enabled by remotely controlling the PC in which software to control the separation arm and to monitor webcam vision are installed, by using the "Remote Desktop."

13.4 Separation Experiment

13.4.1 Experiment

In the experiment, LCD (liquid crystal display) and battery are detached from the sample mobile phone and then shredded by a rotary mill. After shredding, the particles are supplied to the conveyor by a group of certain amount of particles one by one. The amount per one group is determined based on work rates. The amount 102.8 g which is the average weight of a mobile phone was grouped to a certain amount and supplied once per 3 s. The total amount is supplied during 6 min, 3 min, and 2 min. Average time of manual disassembly is about 3 min. The conveyor speed is set to 4 cm/s. Valuable parts are mainly contained in PCB (printed circuit board) origin particles. But, other parts might be also separated if the particles seem valuable.

13.4.2 Experimental Result

Figure 13.5 and Table 13.1 shown next are the result of the remote separation experiment regarding valuable metals. The viewgraph compares the recovery rates of various metal elements separated by remote separation. Regarding Al, Cr, Fe, Ni, Cu, Zn, and Sn, recovery rates were rather high. The figure shows that the most of the metal elements are contained in the separated particles that were recognized as

Fig. 13.5 Schematic view of the remote controlling system

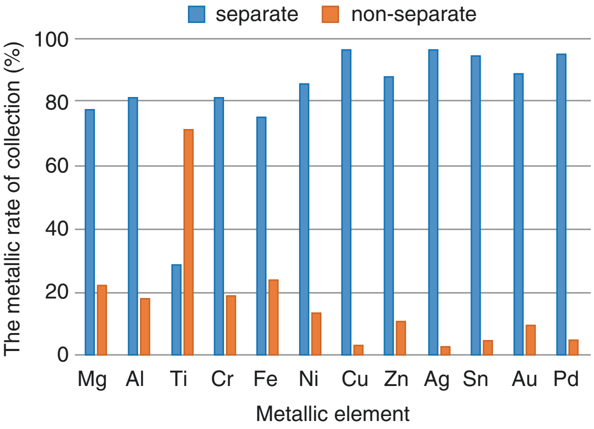

Table 13.1 Recovered amount of various metal elements by remote recycling

Metal element	Separated (g)	Non-separated (g)
Mg	0.290274	0.08384
Al	4.769343	1.07888
Ti	0.52177	1.291257
Cr	0.843329	0.197567
Fe	2.192544	0.708791
Ni	1.15544	0.189334
Cu	10.59226	0.378028
Zn	0.585476	0.075757
Ag	0.059993	0.00215
Sn	0.45514	0.026148
Au	0.035072	0.00405
Pd	0.030097	0.00167

valuable parts. On the other hand, “non-separated” means the particles are recognized as no valuable parts. Recovery rates were also high for precious metal such as Ag, Au, and Pd. However, regarding Ti, the recovery rate was not enough. It is supposed that Ti is mainly included in tip ceramic capacitors. But, ceramic capacitors are hardly recognized as metals by a webcam via Internet. For other elements, the recovery rates were high enough, and it can be concluded that remote separation can separate valuable metals well via Internet.

13.5 Conclusion

In this study, toward reduction of recycling cost, remote recycling technique was considered. In order to put the concept into practice, objectives of the study were to redesign the separation mechanism and develop new algorithm of control mechanism. In our previous study, the system controller was using two different control software for the linear actuator and the robot arm. In this study, the controller was modified to control two motions synchronously. The basic structure that consisted of the lower structure by a linear actuator and the upper structure by a robot arm has not been changed. But, the motion created by the servomotor was changed to separate target particles more smoothly.

By using remote separation, the work time per a mobile phone was much shorter than that of taking out PCB by manual disassembly. Roughly shredded and separated particles showed rather good recovery rates for Ag, Au, Pd, Cr, Ni, Cu, Zn, and Sn. Recovery rates of the metals measured by XRF (X-ray fluorescence) analysis were over 85%. However, for Ti, since the recovery rate was insufficient, it is necessary to adjust the location of the webcam, type of the light, and so on.

These results led us to conclude that remote recycling is useful in reducing the labor cost of intermediate process of recycling, enhancing the efficiency, shortening the time of separation, etc.

Future work is to consider a better way to recognize metal elements that do not have glare with high recovery rate.

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Chapter 14
Examination of Effectiveness of Remote Recycling Through Material Composition Measurement of Used Small Electronics

Kenta Hirose, Akihiro Oikawa, Jun Oki, Kenta Torihara, and Nozomu Mishima

14.1 Introduction

In Japan where natural resources are not rich, recycling of precious and critical metals from used products is important. Although a legislation of recycling of small-sized home appliances has been enforced from 2013, return rate of such used products is very low and needs some countermeasures. Especially, reduction of the cost of recycling process is very important. Based on the situation, the study focuses on how to extract useful resources from used small electronics. As one of the methods, the study has proposed a new recycling method named remote recycling. In the sequential procedure of the method, the used products will be shredded first, and valuable parts are screened from the particles. Although this screening process is very important to increase metal density, it sometimes can be a cost driver of the recycling process. Although the cost issue has not been examined quantitatively, remote recycling can be an idea to reduce such cost for screening by operating the system from remote places where labor cost is relatively cheaper. Plus, there is an advantage that the operator is not required to have special knowledge.

In the previous studies [1–3], the author's research group has tried to measure material compositions of screened particles and clarified that the method has a certain effectiveness. However, the metal densities may vary due to products. In addition, metal contents may change through time. In order to answer these research questions, the study compares metal compositions of other small electronics with those of mobile phones and also tries to compare material compositions of manually disassembled printed circuit board (PCB) with remotely separated particles. Through these efforts, the paper tries to prove that the concept is useful for any kinds of small electronics.

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The main objective of the paper is to check the technical feasibility of remote recycling by measuring material composition and estimating recoverable value of metals in the selected parts of various electronics.

14.2 Overview Remote Recycling

14.2.1 General Concept

The objective of proposing the concept named "remote recycling" is to reduce the cost of intermediate process [4] of recycling that requires considerable labor cost and to increase the flexibility of the recycling process corresponding to many types of electronics. In Japan, or in every other country, establishment of circular economy through recycling of used products is an emerging problem. However, when the amounts of treated products increase and the complexity of recycling process increases because of requirement to recover many elements of metals, increase of product types, and so on, it might be difficult for the current recycling industry to respond to such situation. It will be important to consider a way to ease the situation. The image of the concept is shown in Fig. 14.1.

14.2.2 Setup of Remote Recycling

The separation mechanism consists of a linear actuator (Misumi Corp. RS306B) and an arm to push out selected particles. The arm is controlled up and down synchronously to the linear motion by a servomotor connected to a microcomputer

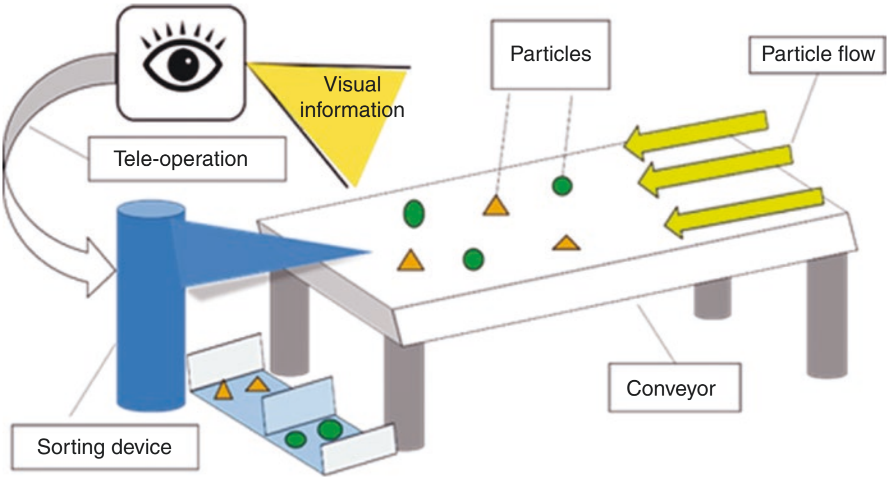


Fig. 14.1 Schematic view of the concept "remote recycling"

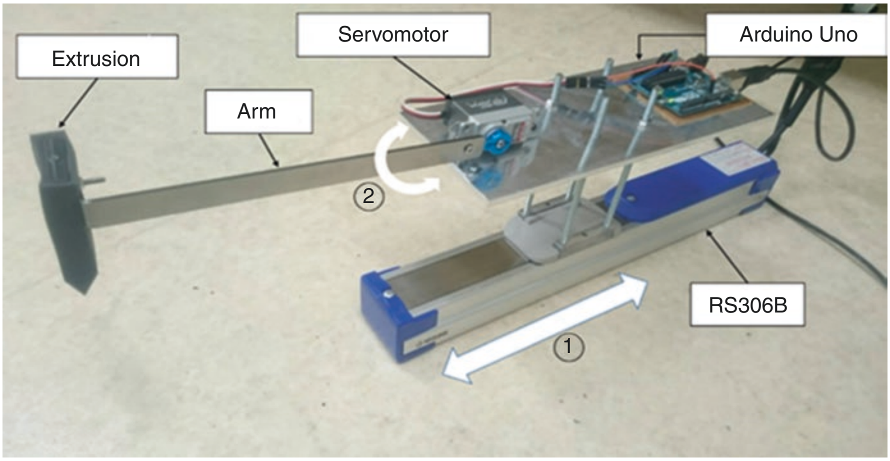


Fig. 14.2 Mechanism for screening

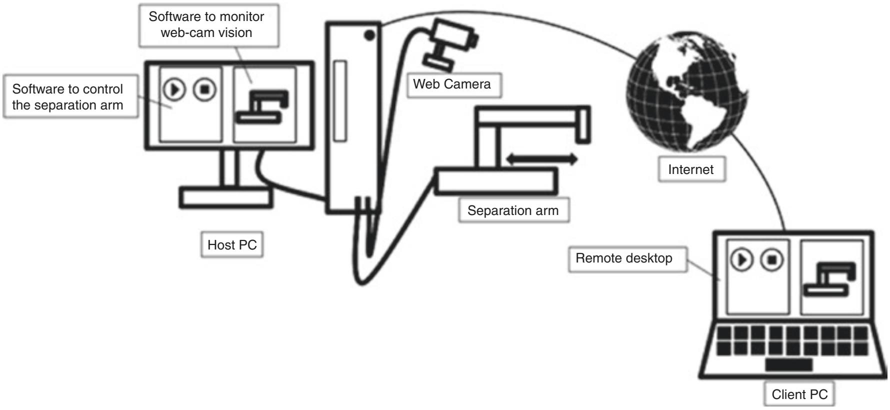


Fig. 14.3 Schematic view of the remote control system

board called Arduino Uno. This is to push out valuable particles without touching unnecessary particles and to return to the initial position after one sequence (Fig. 14.2).

14.2.3 *Tele-operation system*

In the tele-operation experiment, Google Chrome Remote Desktop will be used to control the on-site computer connected to the separation arm from a remote host. The control will be carried out via the Internet. Figure 14.3 shows the schematic view of the experimental setup utilizing the remote desktop. Figure 14.4 shows the display image of the control software.

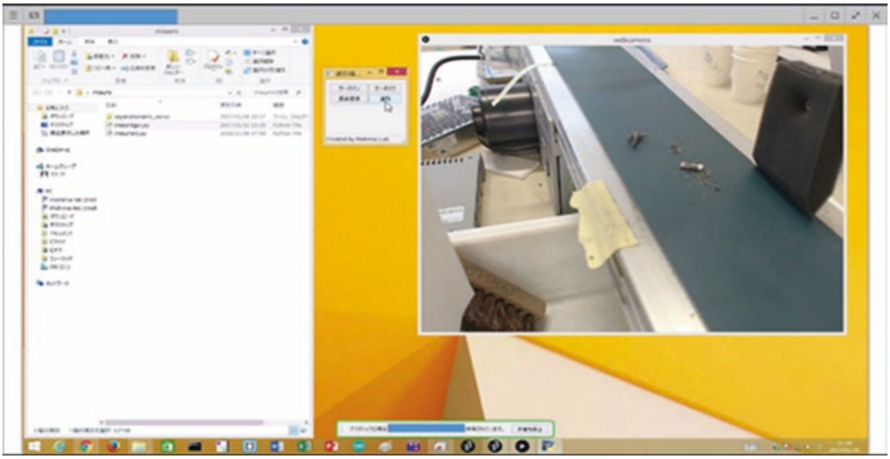


Fig. 14.4 View of the computer display with control software

14.3 Experimental Results

14.3.1 Overview of the Experiment

In the experiment, different items of used small electronics are shredded by a rotary mill. Then, the crushed particles are separated by remote recycling. After the separation, each group of particles will be measured using X-ray fluorescence analysis. In comparing the material composition of selected particles and non-selected particles, or different types of electronics, the separation experiment and measurement were carried out three times for each specimen.

14.3.2 Results of the Experiment

Particles are supplied to the conveyor in every 3s. When the operator thinks that the particles contain valuable metals, the operator pushes out the particles to the recycling bin, and the particles are named “separated.” If the operator thinks that the particles do not contain valuable metals, the particles pass by the separation arm, and such particles are named “non-separated.” In the first experiment, two mobile phones were used. One was a feature phone and the other was a smartphone. Year produced, weight, and weight of printed circuit board (PCB) are shown in Table 14.1. The phones were shredded by a rotary mill until the particles become smaller than 8.0 mm square. Table 14.2 shows the result of screening by remote separation.

In the second experiment, other small electronics were also used. A portable game machine and a digital camera were compared. Table 14.3 shows the fundamental data of each product. The experimental procedure was the same as the first

Table 14.1 Specimen for the first experiment

Product type	Year	Weight (g)	PCB weight (g)
Feature phone	2010	109.566	21.331
Smartphone	2011	87.037	20.631

Table 14.2 Result of the first remote recycling experiment

Product type	Separated weight (g)	Non-separated weight (g)	PCB weight (g)
Feature phone	30.525	21.617	52.142
Smartphone	20.336	18.784	39.12

Table 14.3 Products for the second experiment

Product type	Year	Weight (g)	PCB weight (g)
Feature phone	2009	112.509[a]	23.735
Portable game machine	1996	126.111[a]	49.355
Digital camera	2007	121.746[a]	15.147

[a] Excluding batteries

Table 14.4 Result of the second remote separation experiment with comparison of different product types

Product type	Separated weight (g)	Non-separated weight (g)	PCB weight (g)
Feature phone	69.326	39.79	109.116
Portable game machine	44.855	60.258	105.113
Digital camera	68.651	50.821	119.472

Table 14.5 Basic data of the specimen for the third experiment

Product type	Year	Weight (g)	PCB weight (g)
Portable game machine	1997	125.871[a]	49.355
Desktop game machine	2004	126.111[a]	160.866

[a] Excluding batteries

Table 14.6 Result of the manual separation experiment

Product type	Separated (g)	Non-separated (g)	Total (g)
Portable game machine	56.755	55.677	112.432
Desktop game machine	499.254	310.336	809.59

experiment. But, the shredding was carried out by a hand crusher. Groups of crushed particles were supplied to the conveyor every 3 s, and the average weight per group was approximately 1.7 g. The other conditions were the same as the first experiment. Table 14.4 indicates the data after separation.

The third experiment was also carried out to compare the efficiency of remote recycling with that of manual disassembly plus manual separation. The basic data of the specimen is shown in Table 14.5. After disassembly, metal parts and nonmetal parts were separated manually. The result of the separation is shown in Table 14.6.

14.3.3 Discussion Regarding Metal Recovery

Figure 14.5 is showing the recovery rate of each metal elements obtained by the first experiment.

In order to calculate the recovery rate, Eq. (14.1) was used.

$$\text{Recovery rate of metals}(\%) = \frac{(\text{Weight of the metal included in the separated particles})(\text{g})}{(\text{Estimated total amount in the product})(\text{g}) \times 100} \tag{14.1}$$

Based on the result of the first experiment, recovery rates were 60–70% for feature phones and 40–60% for smartphones. This means that rather big portion of metals were in the non-separated particles. Au from feature phones and Au and Ag from smartphones are included in the separated particles and non-separated particles almost of the same amount. It means that particles from PCB were not recognized well and cannot be recovered well. The reason of this result was that the metal particles were unrecognizable because the particle sizes were too small. The result let us conclude that shredding by the rotary mill and screening using 8 mm square filter were not suitable for remote recycling.

The recovery rate of each element of the second experiment was shown in Fig. 14.6.

Based on the result, as for some metals such as Ti and Zn, the amount of material included in the non-separated particles was larger than those of separated particles. But, as for valuable metals such as Au, Ag, and Cu, most of the metals included in the three different types of products can be recovered by remote separation. Figure 14.7 also shows the result of a different experiment that compares manual disassembly and remote recycling.

By comparing remote separation carried out in the second experiment and manual separation in the third one that were applied to the same specimen (portable game machine), it can be said that manual separation could recover a larger amount of valuable metals. Plus, most of the carbon, which is supposed to be included

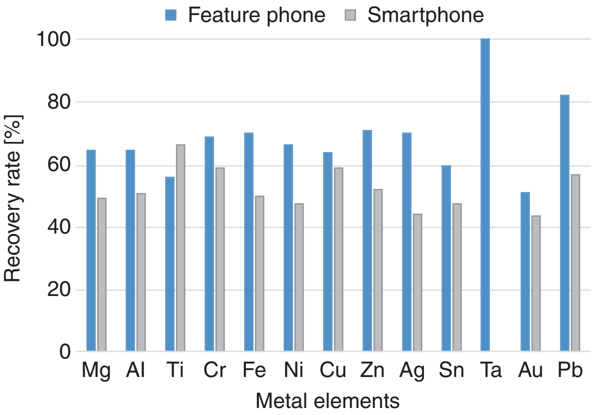


Fig. 14.5 Comparison of metal recovery rates for feature phones and smartphones

Fig. 14.6 Recovery rates of different product types

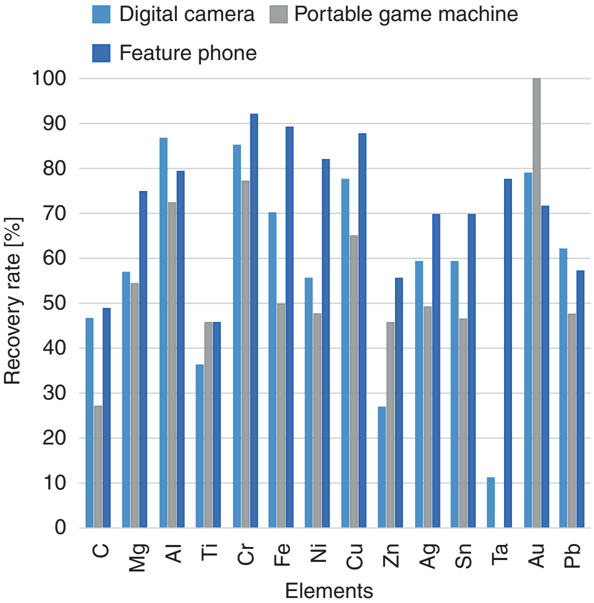
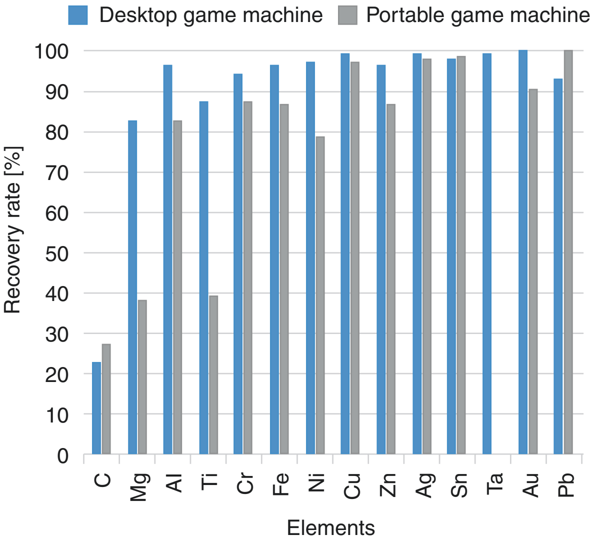


Fig. 14.7 Comparison of manual disassembly and remote recycling



mainly in housing plastics, is well sorted in the "non-separated" group. So, it can be said that, only from metal recovery amount, manual separation is much better than remote separation. However, we should also consider recoverable value of metals. Since most of the value of metals heavily depends on gold, silver, copper, and palladium, the important point is whether the operators can recognize particles that

Table 14.7 Recoverable value by remote recycling

	Manual separation				Remote separation					
	Desktop game machine		Portable game machine		Digital camera		Portable game machine		Mobile phone	
Elements	Selected	Not selected	Selected	Not selected	Selected	Not selected	Selected	Not selected	Selected	Not selected
Mg	0.198	0.041	0.067	0.108	0.051	0.039	0.020	0.017	0.137	0.047
Al	13.519	0.467	0.878	0.184	4.048	0.625	0.885	0.339	1.441	0.371
Ti	0.087	0.012	0.055	0.085	0.052	0.092	0.019	0.023	0.072	0.084
Cr	0.381	0.022	0.109	0.016	0.369	0.063	0.075	0.022	0.783	0.065
Fe	2.298	0.078	0.039	0.006	0.088	0.037	0.033	0.034	0.143	0.017
Ni	2.461	0.069	0.238	0.063	0.675	0.539	0.143	0.157	1.497	0.324
Cu	50.938	0.221	2.607	0.071	2.367	0.692	1.660	0.895	5.856	0.810
Zn	1.424	0.048	0.102	0.015	0.038	0.105	0.051	0.060	0.448	0.358
Ag	22.925	0.069	3.423	0.071	1.715	1.181	1.690	1.756	13.286	5.827
Sn	10.179	0.154	1.705	0.018	0.810	0.562	1.003	1.151	1.478	0.645
Ta	1.575	0.011	0.000	0.000	0.044	0.346	0.000	0.009	0.197	0.057
Au	242.720	0.000	14.212	1.494	56.162	14.942	12.296	0.000	217.509	85.615
Pb	0.077	0.006	0.086	0.000	0.005	0.003	0.052	0.058	0.005	0.003
Estimated value/unit	348.783	1.197	23.521	2.129	66.423	19.226	17.929	4.520	242.852	94.223
Total recoverable value/unit	350.0		25.7		85.6		22.4		337.1	
Value recovery rate	99.7		91.7		77.6		79.9		72.0	
Total recoverable value/kg	430.8	1.5	188.9	17.1	526.7	152.4	147.3	37.1	2025.1	785.7

include such valuable metals easily. Table 14.7 shows the estimation of recoverable value of metals based on the market data [5–11].

14.4 Discussion on Metal Recovery

Basically, Table 14.7 shows that value recovery rates are higher in manual disassembly. However, by taking potentially low recycling cost in remote recycling, the method can be competitive against manual disassembly and separation. Although the recovery rate of remote recycling is relatively lower than that of material separation, remote recycling can be operated from overseas where labor cost is relatively inexpensive or by voluntary work. Plus, manual separation is usually carried out with manual disassembly. So, recycling cost of manual separation can be much higher than remote recycling, and the recovery rates of remote recycling themselves have reached nearly 80% and were rather high.

As for the comparison of products, the measurement result evidently shows that mobile phone has the largest material value. Since in a previous survey [12] material value of a mobile phone is said to be around 150 JPY, more than 300 JPY seems a little too high. It might be due to some deviation in the sampling. But still, it is possible to say "mobile phone is the most important target to collect for material recycling," both for included material amount and number of production per year.

14.5 Conclusions

In this study, the concept of remote recycling which was proposed by the author's research group was examined through different types of experiments. The result showed that recovery rates of metals in remote recycling were 10–20% lower than those of manual disassembly plus manual separation. However, basic recovery rates especially for valuable metals such as Au, Ag, and Cu were rather high and reached about 70–80% for different kinds of products. Although the recovery rates are smaller, since remote recycling is useful in reducing recycling cost, it is a useful method for intermediate process of recycling because lower recycling cost may reduce the economical barrier to engage on recycling of small electronics and may increase the return rates of the products. So, even if the recovery rates are low, high return rates can override the low technical recycling rate. Although a precise feasibility study regarding economic benefit has not been carried out yet, the results shown in this paper were enough to say that remote recycling is technically feasible and the technical recycling rate can be improved by design improvement of screening mechanism, remote operation method, and so on.

As for the future work, it is necessary to examine whether the concept can be applied to other types of products such as microwave ovens, audio devices, etc. Lastly, further investigations regarding material compositions of various types of products are useful, since such information can be useful in determining prior target of used product collection and proper strategies corresponding to the targets. In addition, a more detailed cost-profit analysis, considering not only labor cost but also facility cost, utility cost, operator training cost, and so on, will be necessary.

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Chapter 15
Disassembly Support for Reuse of Mechanical Products Based on a Part Agent System

Atsushi Nagasawa, Yuki Fukumashi, Yoshinori Fukunaga, and Hiroyuki Hiraoka

15.1 Introduction

The effective reuse of mechanical parts is important for the development of a sustainable society [1]. To realize effective part reuse, it is essential to manage the individual parts of a product over their entire life cycle because they have different reuse histories. However, it is difficult for manufacturers to predict such information owing to the uncontrollable and unpredictable diversity of user behavior. Based on these considerations, we propose a scheme whereby a part "manages" itself and supports user maintenance activities.

For this purpose, we are developing a network agent called a "part agent" that manages its corresponding part [2]. It is programmed to follow its real-life counterpart throughout its life cycle. A part agent collects the information related to its counterpart through the network and provides the users with appropriate instructions for reusing it to promote the circulation of reused parts.

A part agent proposes the reuse of its associated part by evaluating the collected information such as the operational history and deterioration of the part [2]. Because a product must be disassembled to extract the parts to be reused, a part agent shows a user how to disassemble the product and extract the part when the user agrees to the reuse. This paper describes a function that generates the disassembly procedure of a product that defines the sequence to extract its parts and another function that displays the instructions by overlaying them on an image captured by a camera. The former is based on predefined product model data and disassembly order data that preset a disassembling order for extracting each part. In the next section, we present the part agent system that is under development. The scheme of the disassembly support system including the representation of the assembly data of the product and generation of the disassembly instructions is described in Sect. 3. A prototype

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system that we developed and its experimental results are explained in Sect. 4. It is to be noted that destructive disassembly must be considered for reusing a part. Therefore, we designed a concept of supporting destructive disassembly by a user. This is described in Sect. 5. Section 6 concludes the paper.

15.2 Part Agent System

A part agent manages all the information regarding its corresponding part throughout its life cycle. The proposed scheme assumes a spread of networks and high-precision radio-frequency identifier (RFID) technology [3].

A part agent is generated when a part is fabricated and an RFID tag is attached to this part. The part agent uses the RFID tag for tracking the life cycle of the part through the network. We chose an RFID tag for identification because RFIDs have a higher resistance to a smudge or discoloration than printed bar codes and will operate throughout the life of a part.

Figure 15.1 shows the conceptual scheme of a part agent. The part agent communicates with various functions within the network and collects the information required to manage its corresponding part such as product design information, predicted deterioration of parts, logistic information, and market information. It also

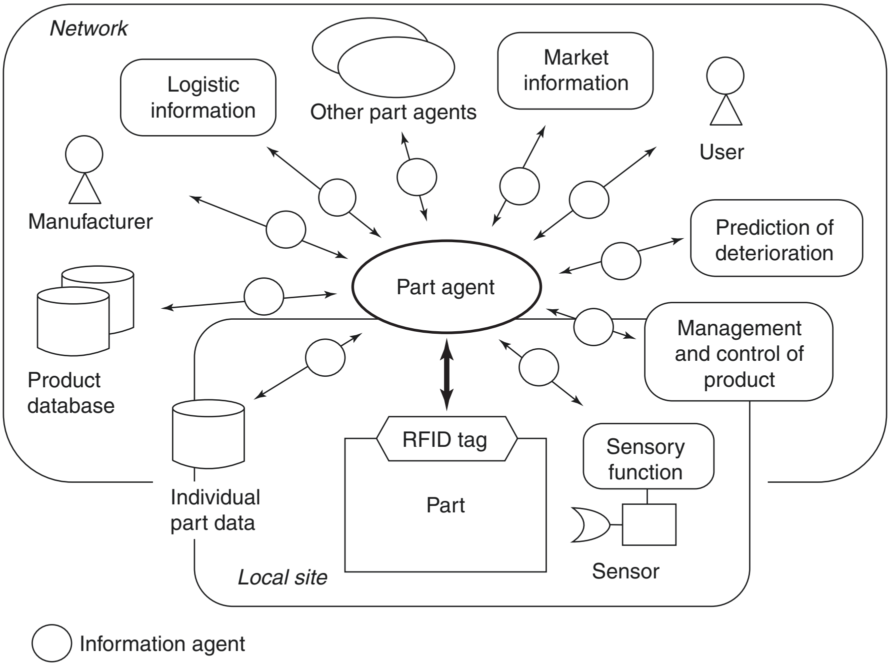


Fig. 15.1 Conceptual scheme of a part agent

communicates with on-site local functions such as sensory functions that detect the state of the part, storage functions for the individual part data, as well as management and control functions of the product. The communication is established through information agents that are subordinate network agents generated by the part agents [4].

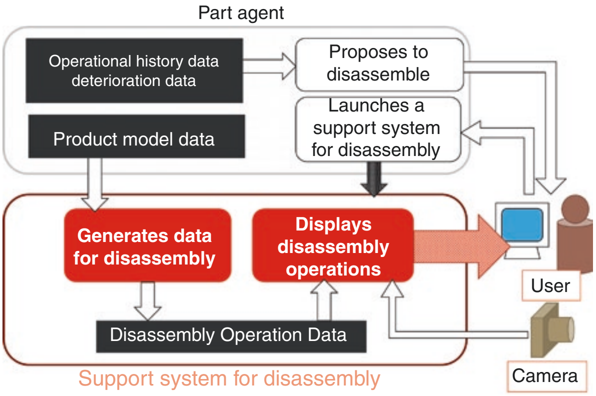
15.3 System for Generating Product Disassembly Instructions

Figure 15.2 displays our proposed scheme to support the disassembly of a product. Herein, a part agent proposes the reuse of the corresponding part by predicting its future state based on the current level of deterioration, its operational history, market information of new/used products, and preferences of the user. When a user accepts this suggestion, the agent launches the support system for disassembly. This support system receives the product model data and disassembly order data from the agent and generates the disassembly procedure data to support the disassembly. The disassembly order is the order in which a product is disassembled. It is represented by a sequence of identifiers of the parts to be extracted. We assume that this order is generated when the assembly is designed and is provided to the part agent. The disassembly procedure is the sequence of disassembly operations that must be performed to disassemble a product. For every part in a disassembly order, necessary disassembly operations are generated using the product model data.

Based on the disassembly procedure data, the system displays the instructions for the disassembly by overlaying them on an image captured by a camera.

Product model data is necessary for generating the disassembly operations and displaying the disassembly instructions on the image of the actual product. We developed a representation of the product model using two data structures focusing

Fig. 15.2 Scheme to support product disassembly



on the assembly. They represent the structure of the assembly and connections between the parts.

L.S. Homem de Mello [5] proposed a relational model graph to represent the contacts and attachments between the parts in an assembly. We designed tree and graph structures for the part agent system. They include the information of the location, shape, and connections of the parts.

Figure 15.3 presents a representation of the assembly structure. This tree structure provides the configuration of the assembly with the positions and postures of all the assembled parts. In this figure, a node represents an assembly, a subassembly, or a part; and an arrow denotes the relation between the assembly and a component. Each part includes the shape data in its local coordinate system. A node contains the coordinate transformation from its local coordinate system to that of its parent node. The parts are connected in the assembly. A portion of the shape of a part that is connected to another part, such as a pin, hole, and screw, is called as an assembly feature. An assembly feature also includes the coordinate transformation to the part it belongs to.

Figure 15.4 displays a representation of the connections between the parts. This graph structure shows the connections between the assembly features of the parts and its states. Each connection includes a pair of assembly features and a type of assembly relation called "connection property" that connects the features.

The assembly properties are referenced for providing a user with information on the disassembly operations such as pulling a part, turning a part, and removing bolts. When connections of all the assembly features of a part are disconnected from those of other parts, the part is removed from the assembly.

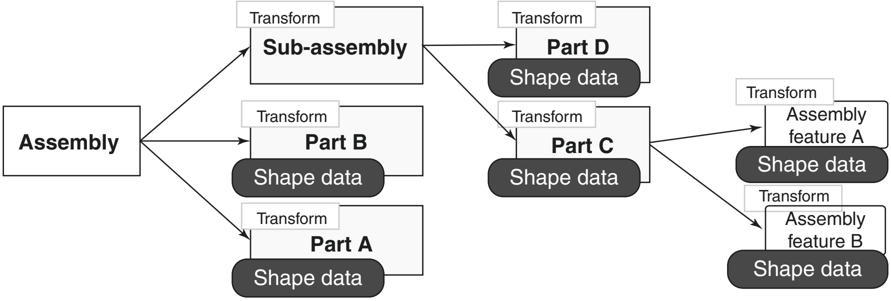
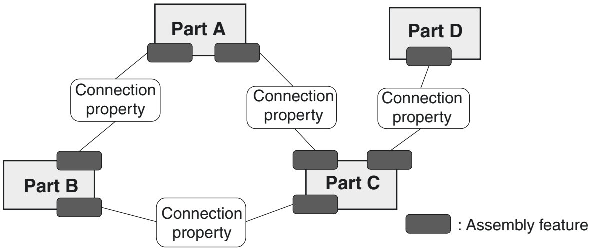


Fig. 15.3 Representation of the assembly structure

Fig. 15.4 Representation of the assembly connections



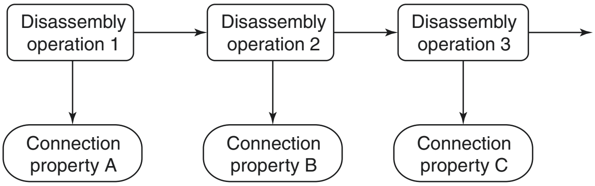


Fig. 15.5 Representation of the disassembly procedure

Figure 15.5 shows a representation of the disassembly procedure that is generated from the assembly connection data and disassembly order data. It consists of the disassembly operations in a tree structure, with each operation having a connection property that must be disconnected for removing the parts according to the disassembly order data. The system displays the instructions for the disassembly operations based on this data.

Each part agent includes the assembly structure and assembly connections of its real-life counterpart. When a part agent launches a disassembly support system, it sends this product model data to the system. Subsequently, the system generates the disassembly procedure based on the assembly connections and calculates the global positions of every part from the assembly structure. Using these results and a marker recognized in a captured camera image, the system displays the disassembly instructions on the image.

Figure 15.6 is a flowchart of an example scheme of the support disassembly of a pinhole connection in the prototype system described in the next section. The arrows identify the pull direction using the transforms of the feature, part, and upper one in the assembly structure tree.

This example scheme has the following steps for displaying the information:

1. Generate the disassembly procedure.
   The disassembly procedure is generated based on a predefined disassembly order. To extract a part, all the connections of the part should be removed. To remove each connection of a part, a corresponding operation is generated based on the connection property and is added to the procedure.
2. Obtain the next connection property.
   Information to support the disassembly is presented to a user based on the generated disassembly procedure. Each operation in the disassembly procedure has a target connection property to be removed. For each connection property, such as a pinhole connection, the corresponding information is generated and presented as follows.
3. Determine the parts related to this connection.
   The system contains the assembly model of the product to be disassembled that includes its assembly structure and connections. A part that contains the connection property to be removed is identified based on this model information.
4. Determine the parts related to this connection.
   The system contains the assembly model of the product to be disassembled that includes its assembly structure and connections. A part that contains the connection property to be removed is identified based on this model information.

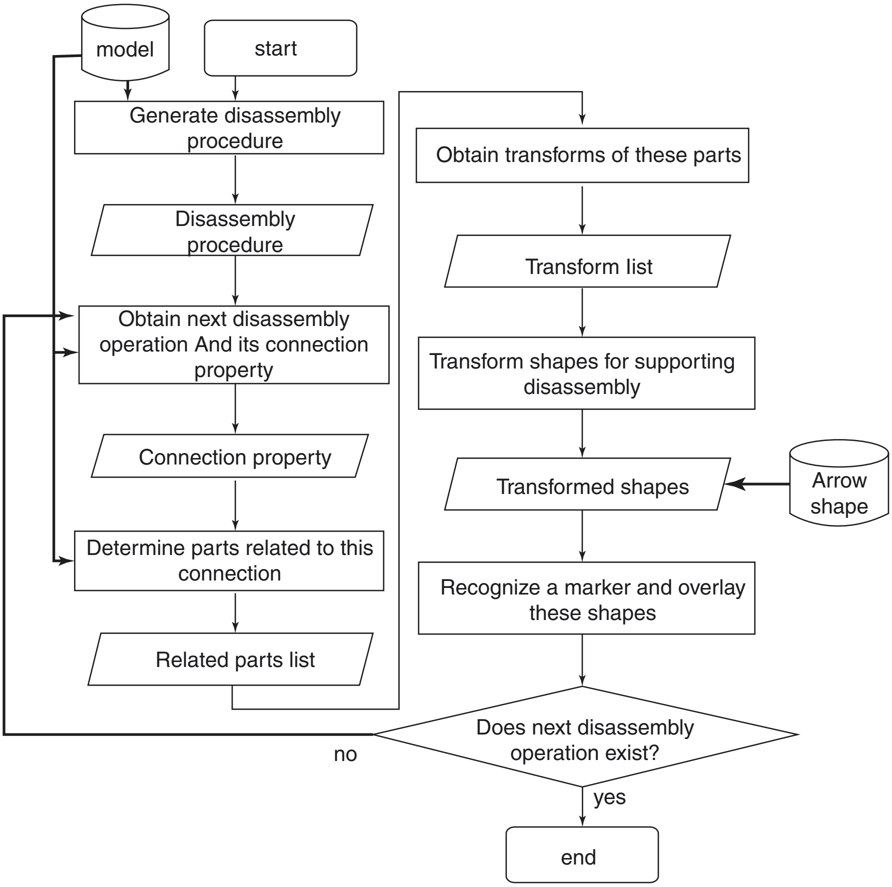


Fig. 15.6 Example scheme to support disassembly of a pinhole connection

5. Obtain the transforms of the parts.
   As described previously, each part includes a coordinate transformation that represents the current position and posture of the part.
6. Transform the shapes to support the disassembly.
   Shapes such as an arrow should be appropriately displayed in the local coordinate system of the part to show a user the necessary motion of the part to be extracted. These shapes are transformed based on the transformation of the part.
7. Recognize a marker and overlay the shapes.
   These shapes should be displayed relative to the real coordinate system. The real coordinate system is calculated by recognizing a marker included in an image captured by the camera. Using this information, the system displays correctly the shapes for the instructions for the disassembly operations by overlaying them on the acquired image.

15.4 Experiment for Disassembly

We developed a prototype system to support disassembly and the required data structures in the Java language. The system uses OpenCV, an open-source computer vision software library, for marker recognition in a camera image. To test this prototype system, we constructed a simple example assembly and generated its product model data.

The example assembly consists of two parts, Part A and Part B, as shown in Fig. 15.7. A hole of Part A and pin of part B are connected. The corresponding model data is presented in Figs. 15.8 and 15.9. The shapes of the parts and assembly features are described in their own local coordinate systems, as shown in Fig. 15.7. For conducting the experiment, we used the model data as inputs and obtained the system generating disassembly operation for extracting Part B.

The system loads the assembly structure and connection data and generates the disassembly procedure. For displaying the information, the system obtains the

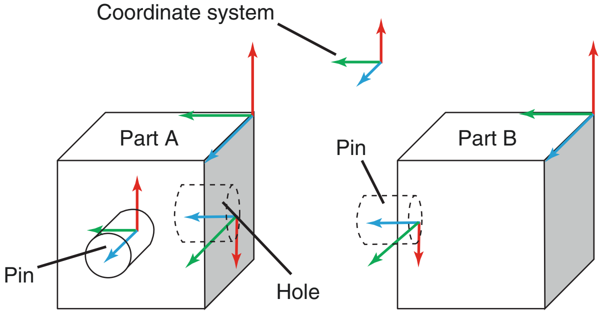


Fig. 15.7 Example assembly

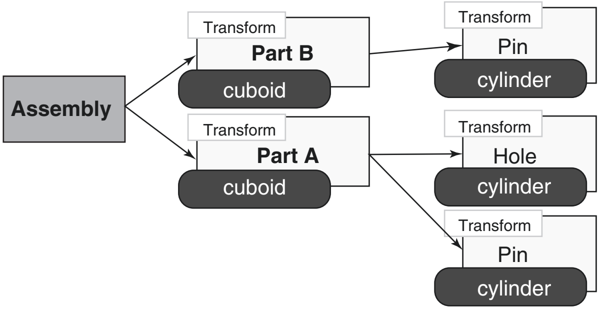


Fig. 15.8 Structural data for the example assembly

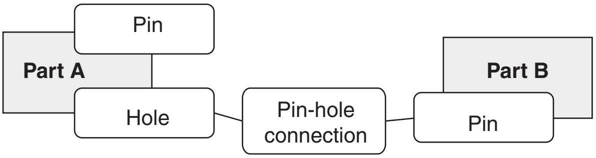


Fig. 15.9 Connection data for the example assembly

shape data of Part B and its transforms that transform the coordinates of the related parts and feature to those of the assembly. The system recognizes a marker in an image captured by the camera and calculates the position and posture of the recognized marker. It shows the shapes to support the disassembly based on the transforms, position, and posture.

The experimental results are displayed in Figs. 15.10 and 15.11. In Fig. 15.10, the shape of Part B and instruction for its disassembly are shown on the captured camera image. The arrow in the figure denotes the direction to pull Part B. Note that a rectangular marker is attached to Part B for the recognition of the position of the assembly. This result shows that the developed function is successful in displaying the disassembly operations by overlaying them on a captured camera image and through marker recognition.

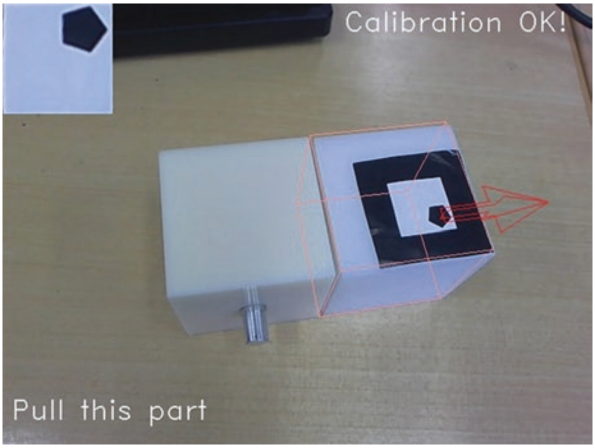


Fig. 15.10 Instruction displayed for disassembly

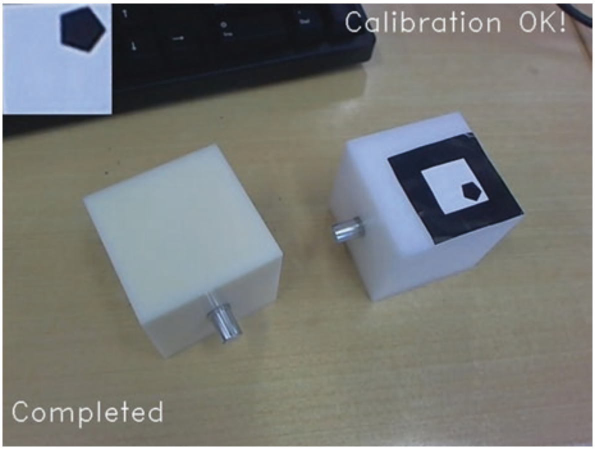


Fig. 15.11 Disassembly completed based on the instruction

15.5 Supporting Destructive Disassembly

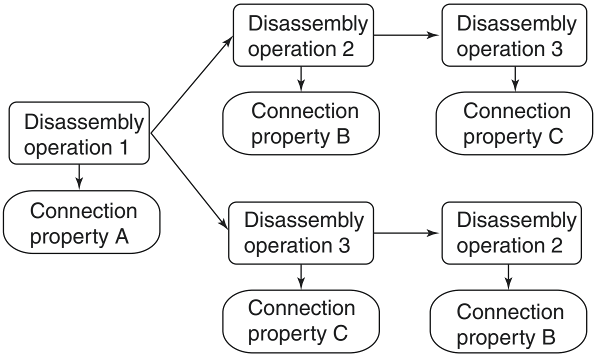
Although the function formulated previously works for new products, we must consider the deterioration of parts for generating the procedure for the disassembly of used products. The deterioration of a part may hamper removing the connections between the parts, which occurs such as in a stuck fastener, distorted connection, and eroded bolt head.

In this paper, to deal with this problem, we propose the following two methods for the improvement of the function to disassemble a product. The first method is to include branches in the disassembly order of the disassembly procedure to provide an alternative sequence of disassembly operations. If an operation is found to be infeasible during a disassembly process, the system generates another disassembly operation based on an alternative branch sequence in the disassembly procedure. Figure 15.12 shows an example of the branched disassembly procedure. In this procedure there is no precedence between disassembly operation 2 that removes connection B and disassembly operation 3 that removes connection C. When disassembly operation 2 is found to be infeasible in the upper branch of this procedure, the system attempts disassembly operation 3 in the lower branch that may make disassembly operation 2 feasible or may make it possible to extract a target part.

The other method is to propose a disjunction by breaking the connection or the part that blocks the disassembly when no alternative disassembly operation is available. This destructive disassembly is often used in practical situations when the aim of disassembly is to extract only precious or poisonous materials.

Shiraishi et al. [6] developed a method to support destructive assembly in the product design phase by adding split-lines to the shells of a product. A split-line is provided on a shell of a part along which the shell is intentionally made prone to breakage. This leads to easier extraction of a reusable part inside the shell by the destruction of the shell. This method requires modification of the product design and provides the information about the position of the split-lines to a user.

Fig. 15.12 Representation of the disassembly procedure including branches



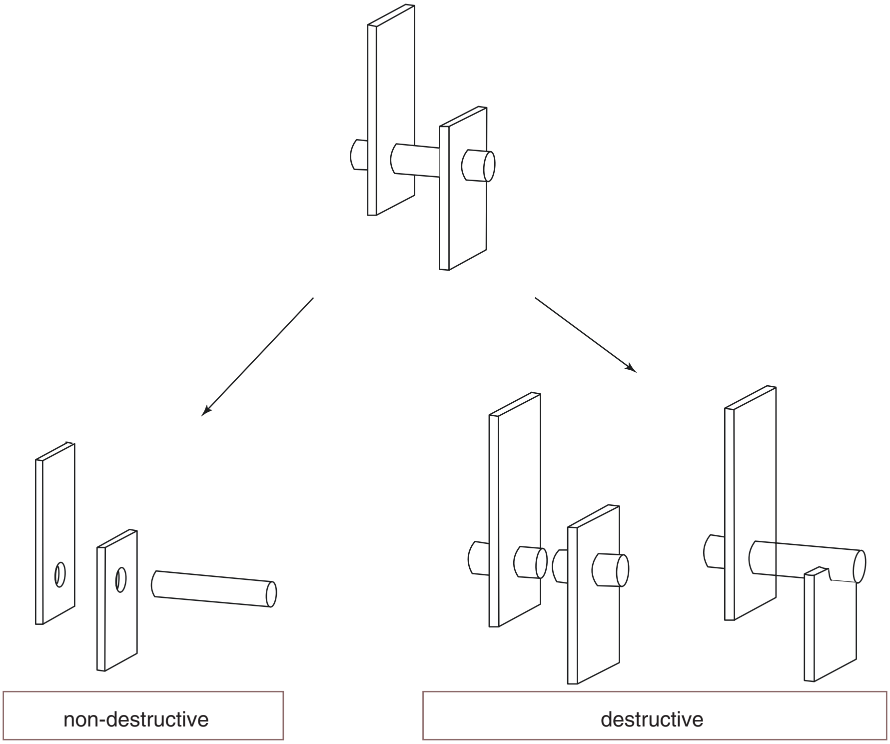


Fig. 15.13 Example of destructive disassembly

We propose a concept of destructive disassembly based on a type of connection property. If a nondestructive disassembly operation on a connection property is not feasible, the system displays the information for the destructive disassembly.

Figure 15.13 illustrates an example of destructive disassembly. In this case, a reusable part can be extracted if a pin shown in the figure is removed. If this pin cannot be removed by nondestructive disassembly, destructive disassembly must be performed. When a user informs the system that nondestructive assembly is infeasible, the system shows the information for the destructive disassembly based on connection properties such as cutting the pin and breaking the hole, as shown in this figure. For this purpose, predefined data for the destructive disassembly is provided to each connection property including the destructive part and its region, with additional information such as split-lines.

An appropriate representation and the contents of the information that are provided to the connection property for destructive assembly are still to be developed. We are also developing a prototype system to evaluate the proposed method.

Each connection property includes the predefined data for destructive disassembly including the destructive part and its region. The system shows a split-line or other information for the destructive disassembly.

15.6 Conclusion

A prototype system for a part agent is developed to support the disassembly of a product using a product model that consists of two data structures focused on the assembly. This system supports users for disassembling a product by displaying instructive information that is overlaid on an image captured by a camera.

The conceptual scheme of supporting destructive disassembly that is designed displays the necessary information based on the connection properties. In the future, it will be implemented in a prototype system.

The remaining issues and future prospects are related to the application of this system in more practical examples that require further investigation of the product models, complex disassembly operations, generation of the disassembly procedure, and display of the disassembly instructions.

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Chapter 16
Metal Recovery from Printed Circuit Boards Using CRT Glass by Reduction Melting

Hiroyuki Inano, Keiichi Tomita, Tatsumi Tada, and Naoki Hiroyoshi

16.1 Introduction

Electrical and electronic waste (e-waste) has been called an “urban mine” recently, because of the higher content of valuable metals than in natural ores. Among e-waste, particularly printed circuit boards (PCB, Fig. 16.1) used in personal computers (PC) and cell phones contain much gold, copper, precious metals, and other valuable components. For example, the circuits contain gold (Au), nickel (Ni), and copper (Cu), and capacitors contain tantalum (Ta), titanium (Ti), and barium (Ba). Among other kinds of e-waste, liquid crystal display (LCD) panels contain indium (In), and magnets in PC hard discs contain neodymium (Nd) and dysprosium (Dy). This has resulted in many metal recovery methods from e-waste being investigated [1–3]. In Japan, the collected PCB is incinerated to concentrate metals, and then the valuable metals are recovered from the concentrate in copper smelting plants.

Among the different kinds of e-waste, treatment of the lead glass used in cathode ray tubes (CRT) of TVs has become an important issue worldwide, and recovery of CRT TV continues at present. In Japan, 1.5 million CRT TVs were recovered in 2015. This is more than the recovery of one million flat panel display TVs, also in 2015 [4]. The glass in the funnel part of CRT (Fig. 16.2) contains up to 25 mass% of harmful lead oxide (PbO), and the lead glass generated from CRT TV tubes cannot be utilized. However, demand for Pb as a raw material for battery electrodes in automobiles and industry is increasing worldwide, and the lead-containing CRT glass has attracted attention as a promising lead resource. Several processes to

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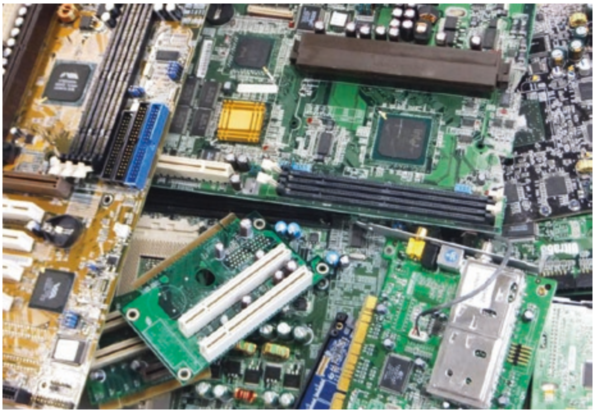

Fig. 16.1 Waste printed circuit boards (PCB) from PC

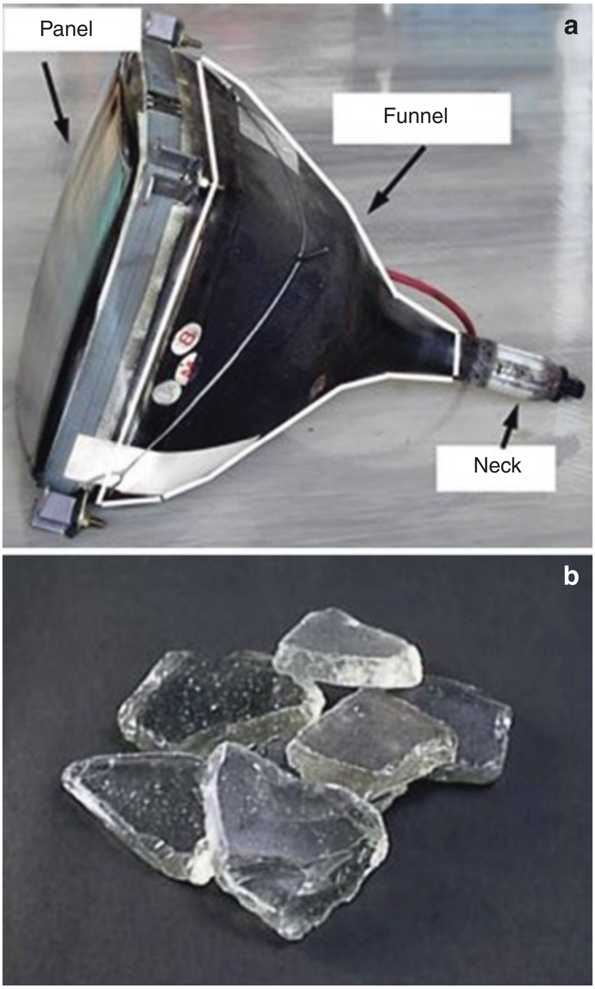

Fig. 16.2 Funnel part (surrounded by white line) of CRT tube (**a**) and its cullet (**b**)

recover lead have been investigated [5–11]. CRT funnel glass is treated at lead smelters, but it needs cost in Japan.

Among lead recovery processes, in particular, reduction melting [5–9] has the advantage to generate lead metal directly, because the generated lead settles and separates from the glass. Molten lead as a collector-metal, generated from CRT glass, incorporates several metals coexisting in the melt undergoing reduction melting. A previous study [12] carried out metal recovery basic experiments by reduction melting that used model lead glass rather than actual CRT glass and added metal agents instead of metals as contained in e-waste, there we reported that Au, Ag, Cu, and Ni could be recovered at rates above 90%, but the recovery rate of In (indium) was lower. Chemical thermodynamics calculations found that the recoverable metals are more difficult to oxidize than carbon monoxide (CO).

In this paper, the authors will present a metal recovery study using reduction melting with actual CRT glass and actual PCB. The recovery rates of several metals were evaluated by analysis of the obtained glass residue and precipitated metals. Metal recovery is discussed by chemical thermodynamics calculations.

16.2 Experimental

16.2.1 Materials

The study used CRT funnel glass containing PbO with grain sizes smaller than 1 mm in the melting tests. The results of the X-ray fluorescence (XRF, ZSX Primus II, Rigaku, Japan) analysis are shown in Table 16.1. The PCB from PC were crushed and freeze ground to grain sizes smaller than 1 mm, and the results of the chemical analysis are shown in Table 16.2. This is a combination of results by X-ray fluorescence (XRF) analysis, inductively coupled plasma atomic emission spectrometry (ICP-AES, ICPS-8100, Shimadzu, Japan), and elemental analysis. Printed wiring boards (bare boards) consist of resin and glass fiber and contain bromine (Br) compounds for fire resistance.

Table 16.1 XRF results of CRT funnel glass

Oxide	Component/mass%
Na_2O	6.3
MgO	1.6
Al_2O_3	3.5
SiO_2	49
K_2O	8.4
CaO	3.8
SrO	1.5
BaO	1.8
PbO	22

Table 16.2 Chemical composition of PCB (0.5 mass% or more and important elements for recovery)

Element	Component/mass%	Analysis method
H	2.1	Elemental
C	21	Elemental
N	1.2	Elemental
O	23	XRF
Al	6.7	XRF
Si	9.9	XRF
Ca	5.5	XRF
Fe	2.3	XRF
Ni	0.42	ICP
Cu	16	ICP
Br	7.9	XRF
Ag	0.085	ICP
Sn	1.1	XRF
Sb	0.52	XRF
Ba	0.58	XRF
Au	0.015	ICP

The tests used Na_2CO_3 reagent (Sigma-Aldrich Japan) as a viscosity-reducing agent to decrease the molten glass viscosity to improve separation of the generated Pb. Activated carbon powder (trade name, Charcoal, Activated, Powder, Wako Pure Chemical Industries, Ltd.) was used as the reducing agent.

16.2.2 Melting Tests

Initially, tests to determine suitable melting conditions were carried out. Volumes of 1 to 5 g of PCB powder and 0 to 3 g of activated carbon were added to 20 g of model glass and 10 g of Na_2CO_3. These were mixed in an alumina mortar and placed in an alumina crucible. A cover with one or two holes was securely adhered to the crucible. The crucible was set in an electric furnace, and then one or two mullite tubes for aeration were joined to the holes in the cover. The sample was heated to 1473 K (1200 °C) at a heating rate 300 K/h. After being kept at 1473 K for 1 h, the sample was cooled naturally to room temperature.

16.2.3 Characterization

The obtained glassy phase was ground and analyzed by XRF.

The metallic phase was cut, and the cut face was observed by a digital optical microscope (KH-1300, Hirox, Japan) and a scanning electron microscope (SEM, JSM-6610LA, JEOL, Japan). The element analysis and mapping were carried out by an energy-dispersive X-ray spectroscope (EDS, JED-2300, JEOL, Japan). The metallic phase was dissolved into aqua regia, and the important metal elements, Au, Ag, Cu, and Ni, in the solution were analyzed by ICP-AES.

16.2.4 Chemical Thermodynamics Calculations

Chemical thermodynamics calculations were carried out to investigate the oxidation-reduction reaction of each element. The thermodynamic database "MALT for Windows" (copyright: MALT group, published by Kagaku Gijutsu-Sha) was used for the calculations. It is essential for elements to be present in the metallic state at 1473 K to be able to recover metals with Pb as the alloy. If metal oxidizes at this temperature, the metal cannot be recovered as the metal oxide dissolves into the glass.

When a metal, M, forms an oxide M_mO_n (m and n are integers), with 1 mol of O_2, the equilibrium of the oxidation-reduction is commonly expressed as.

$$\frac{2m}{n}\mathrm{M} + \mathrm{O}_2 = \frac{2}{n}\mathrm{M}_m\mathrm{O}_n \tag{16.1}$$

The relationship between the changes in the standard Gibbs free energy, ΔG^0, of the equilibria of each component and the temperature was calculated. These results were detailed in an Ellingham diagram.

16.3 Results and Discussion

16.3.1 Melting Tests

Experiments were carried out with fixed amounts of funnel glass and Na_2CO_3 and varying added amounts of PCB and activated carbon.

When 5 g of PCB and 3 g of activated carbon were added, and with 1 hour of aeration at 100 ml/min at 1473 K, activated carbon remained. A similar result was obtained when 1 g of PCB and 3 g of activated carbon were added. As PCB contains sufficient amount of carbon as resin, the additional carbon seems to be excess to reduce PbO in glass.

A starting material mixture with 1 g of PCB and without activated carbon was heated in N_2 flowing at 100 ml/min for 40 minutes. The obtained glass appeared as opaque red, and precipitated metal was observed at the bottom. No carbon remained. The PbO concentration analyzed by XRF was 6.65 mass%, and this established that the PbO in the glass can be reduced by the resin in the PCB without activated carbon addition. The reason why the glass looked red was an effect of Cu particles in the glass. The Cu in the PCB was oxidized to CuO and had dissolved into the glass, and the CuO reduced to Cu. In a previous test [12], the PbO concentration decreased to

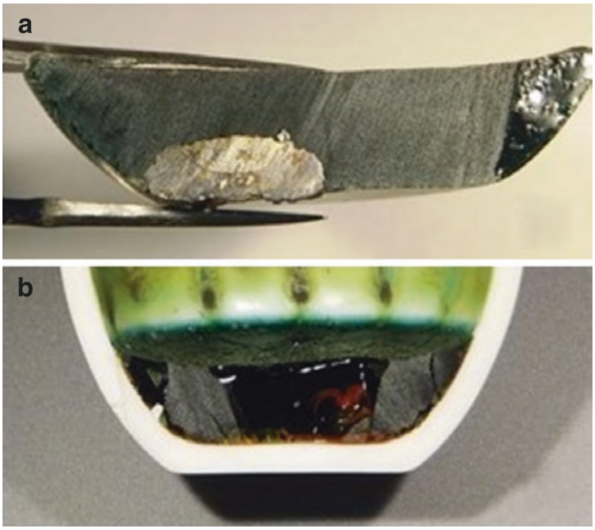

Fig. 16.3 Cross-sectional photographs of reduced (**a**) and oxidized (**b**) samples

1.74 mass% when model glass with added metal agents and activated carbon was melted; in that test the reduction was not sufficient under the melting conditions.

Based on these results, the starting material mixture was heated under the conditions of PCB addition increased to 3 g without activated carbon and a N_2 flow of 100 ml/min for 10 min. The PbO concentration in the glass decreased to 0.57 mass%. When heated under similar conditions without N_2 flow, the PbO concentration was 0.40 mass%. A cross section of the resulting sample is shown in Fig. 16.3a.

Next, a starting material of 3 g of PCB and 1 g of activated carbon was heated without a N_2 gas flow. Carbon remained in the obtained sample, and the PbO concentration was 2.15 mass%. These results show that the PbO contained in 20 g of funnel glass can be reduced by 3 g of PCB and that an excess of activated carbon addition inhibits PbO reduction.

The results indicate that the optimum conditions are a mixture of 20 g of funnel glass, 10 g of Na_2CO_3, and 3 g of PCB heated at 1473 K (1200 °C) without a gas flow. The sample obtained under this condition is termed the "reduced sample."

To compare this, the same material mixture was heated in an airflow of 100 ml/min during heating. Green-colored glass was obtained, and there was no precipitated metal (Fig. 16.3b). The sample obtained under this condition is termed the "oxidized sample."

16.3.2 *Estimates of Elimination Rates of Metals*

Glassy phases of reduced and oxidized samples were analyzed by XRF, and the elimination rates of the metals were estimated based on these results. In the oxidized sample, it is assumed that the added metals remained in the glassy phase without precipitation and volatilization. In the reduced sample, components that were present as metal during the melting were eliminated and alloyed with the Pb generated by reduction of the funnel glass. Among the funnel glass components, SiO_2 and Al_2O_3 are stable and are not reduced, so these amounts do not change in the oxidation and reduction melting. Elimination rates of the metals were calculated from the changes in the metal oxide concentrations with an unchanged SiO_2 concentration. The elimination rate $E_{\mathrm{m,red}}$ (%) for the metal component, m, was calculated by the following equation:

$$E_{\mathrm{m,red}} = \frac{\dfrac{C_{\mathrm{m,ox}}}{C_{\mathrm{SiO_2,ox}}} - \dfrac{C_{\mathrm{m,red}}}{C_{\mathrm{SiO_2,red}}}}{\dfrac{C_{\mathrm{m,ox}}}{C_{\mathrm{SiO_2,ox}}}} \times 100 \qquad (16.2)$$

where $C_{\mathrm{m,ox}}$ and $C_{\mathrm{m,red}}$ are the concentrations of m oxide in the glassy phase of the oxidized and reduced samples, respectively. And the $C_{\mathrm{SiO_2,ox}}$ and $C_{\mathrm{SiO_2,red}}$ are the concentrations of SiO_2 in the glassy phase of the oxidized and reduced samples, respectively. Results of the XRF analysis and elimination rates are shown in Table 16.3.

The oxides that concentration in the reduced sample are smaller than that of the oxidized sample expressing eliminated components. The metals in these eliminated components have formed alloys with lead, and the metals involved are Ni, Cu, Sn, and Pb. The elimination rates of Ni, Cu, and Pb were above 90%. That of Sn was above 70%. The concentrations of the other oxides were similar in the oxidized and reduced samples.

Table 16.3 XRF results of glassy phase of oxidized and reduced samples and elimination rates

	Reduced sample	Oxidized sample	Elimination rates
Oxide	Mass%	Mass%	%
Na_2O	32	26	−5.7
MgO	1.6	1.3	−5.7
Al_2O_3	5.1	5.2	16.7
SiO_2	44	37	−0.2
K_2O	6.8	5.8	0.4
CaO	4.0	3.4	−0.8
TiO_2	0.16	0.15	8.0
Fe_2O_3	1.5	1.3	−2.1
NiO	0.0052	0.065	93.2
CuO	0.043	1.8	97.9
SrO	1.2	1.0	1.4
ZrO_2	0.29	0.23	−4.0
SnO_2	0.11	0.39	72.6
BaO	1.4	1.3	0.6
PbO	0.41	14	97.6

16.3.3 *Characterization of the Precipitated Metal Phases*

16.3.3.1 SEM Observations and EDS Analysis

A microscopic cross-sectional image of precipitated metal is shown in Fig. 16.4. It suggests that the metal is separated into two layers, upper gold-colored and lower silver-colored layers. A section at the boundary area was observed by SEM and analyzed by EDS, with the SEM image shown in Fig. 16.5, upper right is the gold-colored area and lower left the silver-colored area. The result of the EDS analysis is shown in Fig. 16.6. Here, Cu and Sn among the metals contained in PCB were detected in addition to Pb from the CRT glass. From the results of the XRF analysis, Ni was expected to be contained in the metal precipitate, but Ni could not be detected due to the very small quantities present.

Elemental mapping was carried out for the Cu, Pb, and Sn, with the results shown in Fig. 16.7. Here, the targeted elements are shown as bright areas, the top right part shows that there was much Cu throughout this area, Pb was in an island-shaped area in it, and Sn was present throughout. In contrast, the left lower part shows that there was mostly Pb with a little Cu, but Sn was not detected.

16.3.3.2 ICP-AES Analysis

The EDS analysis showed that the precipitated metal included Cu, Pb, and Ni. The metallic phase (4.55 g) was dissolved in aqua regia, and the solution was analyzed by ICP-AES. The target metals were Au, Ag, Cu, and Ni, all of high economic value, and recoverable by the previous reduction melting basic experiments [12].

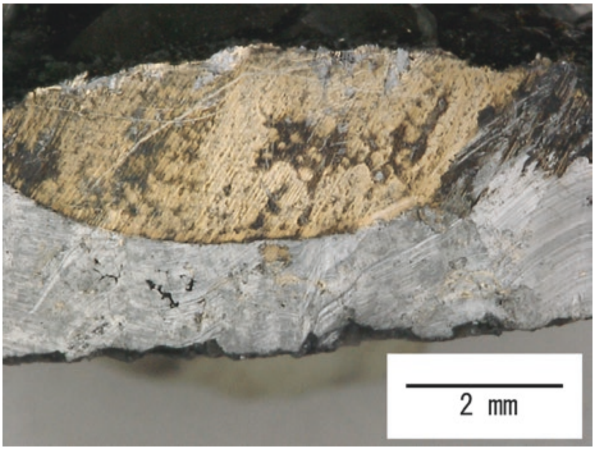

Fig. 16.4 Microscopic cross-sectional image of precipitated metal in reduction sample

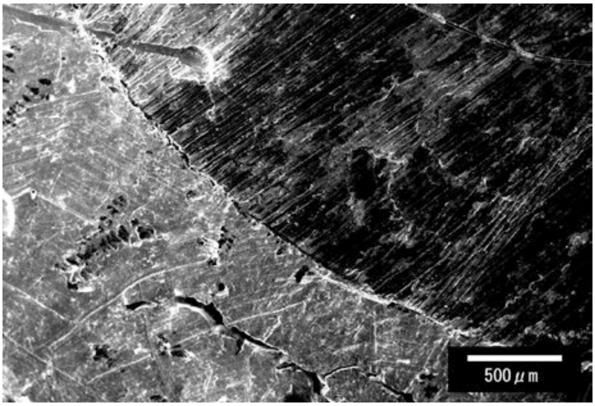

Fig. 16.5 SEM image of precipitated metal

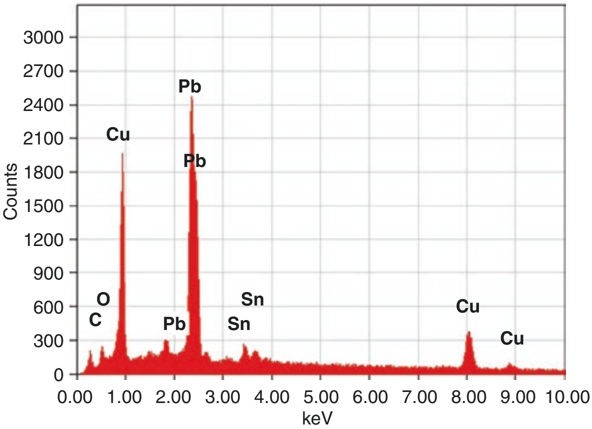

Fig. 16.6 EDS analysis result of precipitated metal

The metal recovery rates, R (%), are calculated from the mass of the metal contained in the precipitate metal, M_{metal} (mg), and that contained in the PCB used as starting material, M_{PCB} (mg), by the following equation:

$$R = \frac{M_{\mathrm{metal}}}{M_{\mathrm{PCB}}} \times 100 \tag{16.3}$$

The result is shown in Table 16.4. The recovery rates for Ni and Cu exceed 100% likely due to errors in the metal distribution in the ground PCB. The recovery rates for Ag and Au are 84 and 73%, respectively, and the results show that Au, Ag, Cu, and Ni contained in the PCB can be recovered together with Pb at high recovery rates.

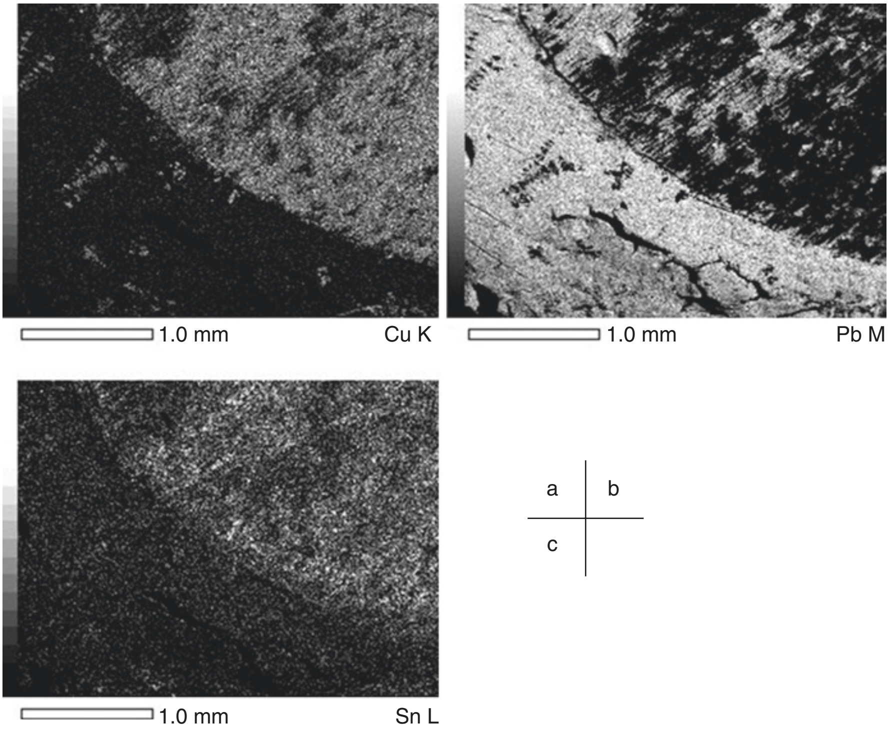

Fig. 16.7 Elemental mapping by EDS of Cu(a), Pb(b), and Sn(c) in precipitated metal

Table 16.4 Results from ICP-AES analysis of dissolved metal phase and recovery rate

	Unit	Ni	Cu	Ag	Au
Concentration in precipitate metal (4.55 g)	Mass%	0.31	11	0.046	0.0073
Mass in precipitate metal	mg	14	50 × 10	2.1	0.33
Mass in additional PCB (3.0 g)	mg	13	48 × 10	2.6	0.45
Recovery rate	%	108	104	81	73

16.3.4 Thermodynamics Calculations for the Metal Recovery

It is necessary for metal to be present in the metallic state during melting to be able to recover the metal by this method. To determine oxidation characteristics for individual metals, the relationship between the change in the standard Gibbs free energy ΔG^0 and temperature was calculated. The main components of funnel glass and PCB were selected for the calculations. The results of the calculations are plotted in an Ellingham diagram in Fig. 16.8. Here, each line indicates a ΔG^0 for a metal, C, or

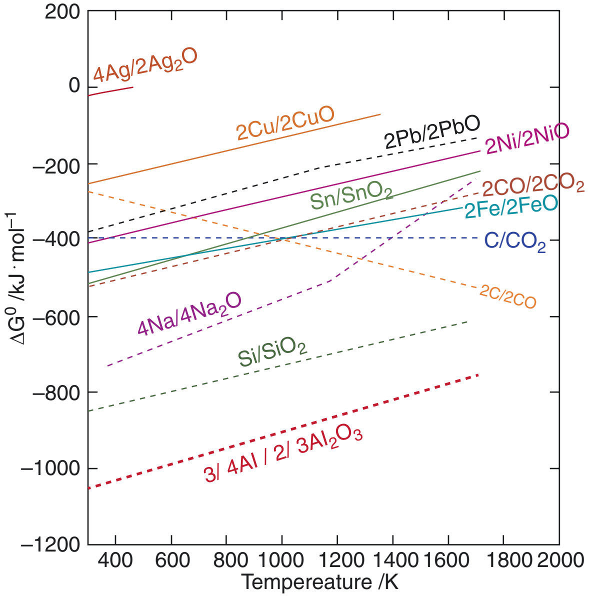

Fig. 16.8 Ellingham diagram of oxidation with 1 mol O_2 for elements contained in PCB and funnel glass

CO, reacted with 1 mol of O_2 and is labeled with a reductant/oxidant pair. For example, the following oxidation-reduction equilibrium,

$$2\mathrm{Pb} + \mathrm{O}_2 = 2\mathrm{PbO} \tag{16.4}$$

is labeled as “2Pb/2PbO.” Solid lines are for metals contained in PCB, dotted lines are for the main components of funnel glass, and broken lines are for C and CO, which are the reducing agents. There is no line for gold (Au) because Au does not react with oxygen.

Reactions with larger negative values of ΔG^0 occur more easily, and such oxides are stable. Oxides plotting higher in the figure are reduced by metals, C, or CO which plot below them. The PCB contains 21% of resin containing C, here employed as a reducing agent.

In the melting tests, Au, Ag, Cu, Ni, and Sn were recovered together with Pb, and in Fig. 16.8, the Ag, Cu, Ni, and Sn lines plot above the CO line, indicating that CO reduces these oxides. The PbO in the funnel glass is reduced by C and CO and is converted to Pb by the following reactions:

$$2\mathrm{PbO} + \mathrm{C} \rightarrow 2\mathrm{Pb} + \mathrm{CO}_2 \tag{16.5}$$

$$\mathrm{PbO} + \mathrm{CO} \rightarrow \mathrm{Pb} + \mathrm{CO}_2 \tag{16.6}$$

The PbO concentration in the glass residue decreased more than in the previous experiments using model glass and metal reagents [12]. There are two possible reasons for this: one is reduction by Si and Al in the PCB. A part of the Si and Al contained in the PCB is in the metallic state and acts as a strong reducing agent. For example, Si can reduce PbO to Pb. This reaction may be expressed as follows:

$$2\mathrm{PbO} + \mathrm{Si} \rightarrow 2\mathrm{Pb} + \mathrm{SiO_2} \tag{16.7}$$

Another possibility for the relatively higher decrease is an effect of $PbBr_2$ volatilization caused by a combination of PbO in the glass and Br contained in the PCB, added as a fire-resistant compound.

As reported in the previous paper [12], Ba and Ti oxidize more easily than C, and so were not recovered by the reduction melting.

Overall, the results of this study show that not all metals can be recovered by this method. However, this process does recover metals of high economic value at high recovery rates, and the method is simple and simply implemented.

16.4 Scenario for e-Waste Treatment by This Method

At present, CRT funnel glass is dismantled and crushed locally and is transported to a lead smelter for treatment, and PCB is treated at copper smelters. When CRT glass and PCB are transported from different locations to these smelters, both valuable metal and larger volumes of waste have to be transported. About 75% (by weight) of funnel glass and 90% of the PCB have low economic value. The process developed here enables valuable metal recovery with the lead by small plants at many locations far from smelters. Lead extraction and treatment to make CRT funnel glass harmless and the metal extraction from PCB can be carried out simultaneously. Glass fiber contained in large amounts in PCB melts together with the CRT funnel glass and forms a glass residue simultaneously. Transport costs to the smelters decrease to become the transport of only the recovered metal containing lead. Glass residue can be utilized in civil engineering materials at the treatment location. Lead refining processes separate Au, Ag, Cu, Ni, and other components. These metals can be sold at high prices. Further, the metal obtained by reduction melting can be refined at each location to extract pure lead and valuable metals.

This process decreases the amount of CO_2 emissions for avoiding long-distance transportation of waste.

16.5 Summary

Metal recovery from urban mine resources was investigated. Metal that contains Au, Ag, Cu, Ni, Pb, and other components was recovered at 1473 K (1200 °C) from the melt of CRT funnel glass and PCB without addition of carbon. Recovery rates of these metals were 70 to 100%. The PbO concentration in the glass residue was smaller than that obtained in tests using model lead glass and metal reagents. This process enables recovery of lead and treatment to make CRT lead glass harmless and simultaneously extract metals from PCB.

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Part III
Sustainable Energy and Policy

Chapter 17
Diffusion Policy Assessment of Solar Energy

Khalid Alrashoud and Ryoichi Nakayama

17.1 Introduction

Renewable energy (RE) has been supported in many developed countries, to address two primary energy-related concerns, namely, energy import dependency and growing greenhouse gas (GHG) emissions. The solar energy integration in seven selected developed and developing countries has been examined in this study. Despite some drawbacks that may have occurred during developing a market for this technology, each of these selected countries has overcome many challenges and made tremendous successes in creating a new alternative energy source. This will ultimately help boost more stable and sustainable economies for their countries and for the global economy across the world. Each country boosted the integration of solar power through a variety of mechanisms and policies seeking an optimal model for its energy mix. The most effective policies and actions implemented to encourage the deployment of solar power in each case will be discussed along with shortcomings to gain insights about the nature of the most affecting factors that may have acted as barriers toward the implementation of this technology. The researcher divided the barriers that are identified in the study into four categories, including technology, policy, financial, and management barriers.

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17.2 Identifying of Terms

In order to better understand each case of the selected countries, the researcher presents the most significant actions made by each country that have positively or negatively affected the development and implementation of solar energy projects. The actions that have positively influenced the implementation of solar energy projects and helped boost and promote this technology are typically referred to as "appropriate actions."

On the other hand, activities that may have caused a stumble or delay in the development of solar energy are referred to as "inappropriate actions." These inappropriate actions are then classified into four approximate categories for the purpose of better understanding the main causes of these issues. First, technology barriers, which indicate failures caused by poor performance of solar systems, include solar panel, inverter, battery pack, controller, etc. Whether the poor performance results from internal factors, such as material defeat, or from external factors, such as harsh weather, it is categorized under the term of "technology." Technology is defined as "Machinery and devices developed from scientific knowledge" [1]. It is also interpreted as "The application of scientific knowledge for practical purposes, especially in industry" [1]. The term policy can be identified as "A course or principle of action adopted or proposed by an organization or individual" [2]. This covers regulatory mechanisms adopted by a government to organize the relationship among electricity sellers, buyers, and end users. It also includes policies made to decrease ambiguity and uncertainties for investors, as well as to set new policies that aim at fostering the attitude of the adoption of solar energy.

As for the term of financial, the current sense of the term can be traced to at least the eighteenth century. "Late Middle English: from Old French, from finer 'make an end, settle a debt,' from fin 'end.' The original sense was 'payment of a debt, compensation, or ransom'; later 'taxation, revenue'" [3]. Finally, management is referred to as the technics used to manage and organize the available resources. English Oxford Dictionaries identified it as "The process of dealing with or controlling things or people" [4]. Whether it is a governmental body, a corporation, or a not-for-profit organization, management indicates the action of administrating the respective organization's resources. It may include the activities of coordinating the efforts of the organization's employees to achieve its objectives within the available resources, such as financial, technological, and human resources. In this paper, the term management may also refer to the end users who make use of services provided by an organization or a firm.

17.3 Methodology and Research Design

The case study approach was chosen to conduct this research. "The case study approach allows in-depth, multi-faceted explorations of complex issues in their real-life settings" [5]. "Case study research, through reports of past studies, allows the exploration and understanding of complex issues. It can be considered as a robust research method particularly when a holistic, in-depth investigation is required" [6]. The seven selected countries are as follows: Germany, Japan, the USA, the UK, Spain, India, and Greece. They were selected based on their rich experience in creating new markets for solar technology and confronting plenty of challenges and difficulties along the way.

17.4 A Case Study on Global Practices of Solar Energy Diffusion

17.4.1 Germany

Germany is one of the major electricity consumers in Europe. In 2013, Germany's electricity production reached 532.2 TWh [7]. The primary energy source in Germany is brown coal with a capacity of 140.7 TWh (26.4%), followed by hard coal, representing 11.1 TWh (20.7%). The third largest energy source in Germany is nuclear constituting 91.8 TWh (17.2%), and then biomass comes fourth, with a 53 TWh, representing 10.0%. Next is wind energy with 51.4 TWh (9.7%), natural gas 33.9 TWh (6.4%), solar 32.8 TWh (6.2%), and hydro 18.5 TWh (3.5%) [7]. Regarding RE market development, Germany has been considered as a successful leading model of transition from depending on fossil fuel energy to the use of RES as a clean alternative source of energy. To understand the factors behind these achievements, it is necessary to know what it results from.

After the Social Democratic-Green government came into office in 1998, a further boost has been given to the comprehensive promotion plan that was launched at the beginning of the 1990s to enhance the utilization of RE. Promotion measures have been enacted to supply 18% of the countries' consumed energy from renewable sources by 2020 [8]. The German parliament passed the binding equalization scheme (EEG) legislation that was amended multiple times between 2000 and 2012 to revise and eliminate quotas on certain technologies. By enforcing this legislation and through other policy adjustments, these procedures were necessary to persevere the rapid expansion of renewable power in Germany, especially with the boom of solar PV applications. In addition, in 2012, the market premium policy for renewable power projects was introduced by the government. This policy indicates that the FiT policy structure will likely shift to other policies, such as the market premium or some other market integration incentives over time. The motivation of introducing such policies was to actively involve renewable energy projects in the electric power market. Hence, premium incentives in Germany are designed to decline gradually over time based on the predetermined and the set market-responsive schedules [9]. In 2012, an amendment to Germany's EEG was made to enable renewable electricity projects to receive adjustable market premiums rather than FiT incentives. The EEG policies have many nuances which made it a complex mechanism [10].

Table 17.1 A summary of actions taken by the government in Germany

Country	Total PV installed capacity (MW)	Appropriate actions taken by government	Inappropriate actions taken by government
Germany	39.700	Transformation from FiT to tender or quota system by 2017 guarantees grid access and uptakes the surplus power	Support unequally split across rare classes made heavy consumers the most levy-exempt
		Set a cap on aggregate solar PV capacity of 53GW	Implemented FiT surcharge on consumers to pay the difference between the fixed price of RE fed into the grid and the sale of RE at the energy stock market
		Mandatory direct marketing implementation	Delay in readjusting FiT's rates

The government has also focused on wind and solar PV projects that can be monitored and managed remotely offering high management fees to incentivize these technologies for more renewable electricity integration. At the same time, the management fee of market premium has been gradually reduced starting from January 2013. This gradual reduction was also applied to the FiT. The main goal of the gradual reduction of this fee is to set FiTs at a level that encourages toward investment in RE projects and expands the market of RE generation while at the same time avoiding nuances of the over-deployment of RE projects, as well as preventing windfall profits for project owners. One approach to stimulate the expansion of RE in Germany is the electricity surcharge which secures the necessary funds of RE incentives by dividing the costs over a larger electricity consumer base. This differentiates Germany from other countries, as it uses federal tax revenues to fund their incentive programs [11]. Table 17.1 summarizes the German government's actions toward the implementation of solar energy.

17.4.2 Japan

After the suspension of nuclear reactors due to the Fukushima plant accident in 2011, domestic energy resources in Japan have dropped down from 20% to less than 9% of the country's total energy use. With its massive energy consumption, Japan ranks the third largest oil consumer after the USA and China in the world. Despite its limited domestic power resources, Japan has actively worked to develop its capability in the energy sector by increasing the use of natural gas and coal, as well as encouraging the use of renewable energy and the efficient consumption and conservation of energy [12].

Since 2011, the government seeks to cover the shortage of energy supply by shifting to renewable alternatives. Both previous governments, as well as the current government, have implemented several reforms and policies to ensure a stable and safe supply of energy without undermining the majority of Japanese who oppose atomic energy. One of the most significant mechanisms is FiT which is a key scheme that was introduced in 2012 following the shutdown of the nuclear reactors. It specifically began in July 2012, obliging companies to purchase electricity generated by renewable sources at fixed rates. The revenue received will then be used to facilitate investment in renewable power generation.

In the middle of 2016, the Ministry of Economy, Trade, and Industry (METI) sought a change of the currently existing FiT system [13]. The new amendments to the FiT system included a significant number of modifications that set more constraints on the existing rules [13]. These constraints include:

- The obligation of conducting inspections and maintenance on a regular basis to ensure a stable supply.
- To submit production incurred costs and install capacity to METI at fixed intervals.
- To generate power in a manner that ensures grid stability.
- To suspend all facilities that have ceased to be used to link with a utility grid.
- To initiate new supply with a fixed time frame.
- To adhere to all land-related laws and safety regulations.
- To preserve to signage on site indicated in the criteria list that must be met by the generation/operation company to be certified.

The new amendments give METI the authority to revoke the infringing plant's certification if it was approved by METI or any other government agency if one or more of the requirements are not satisfied. Moreover, it enables METI to oblige project developers/operators to rectify their infringing equipment that has been in use. It has been reported that some of these new constraints doubled up on other legal requirements, resulting in institutional issues. Nevertheless, it is expected that METI will show less tolerance to operators who are not on track to contribute to its objectives of building a robust and diversified electricity supply [13]. Table 17.2 presents actions made by the Japanese government regarding the implementation of solar energy projects.

17.4.3 The USA

The USA is considered as the world's second largest energy consumer and producer after China. The primary source of energy in the USA is petroleum, followed by natural gas and coal. It also generates power from clean energy sources, such as biomass, wind, solar, and nuclear power. In terms of renewable energy, the USA has enacted several policies and mechanisms to boost the development of RE to cope with the increasing demand on energy. Renewable energy standard (RES), which is also known as renewable portfolio standard (RPS), is one of the most successful policies implemented to enhance renewable energy projects in the USA. RPS was

Table 17.2 A summary of actions taken by the government in Japan

Country	Total PV installed capacity (MW)	Appropriate actions taken by government	Inappropriate actions taken by government
Japan	39.700	Low-interest loans	Immediate suspension with no previous notification for new projects troubled developers and operators
		Design comprehensive education and awareness programs across the country	Awarding contracts to some companies without verifying their technological and financial abilities
		Institute the RPS Law that obliges electric power companies to expand the use of electricity generated by renewable energy sources	Awarding contracts without specifying a time frame to implement RE projects

combined with federal production tax credit shaping an effective tool to catalyze the utilization of renewable energy technologies. Driven by such combined tools, States have designed them to encourage the adoption of a certain technology (e.g., wind, solar) and provided carve-out provisions to ensure a share of electricity generated from that particular technology. With the flexibility offered by RPS, the States have the freedom to apply the requirement of RPS either to the investor-owned utilities or to all its existing utilities. Moreover, States have the right to determine the eligibility of each type of renewable energy technologies to be counted to fulfill the RPS requirements [14].

Solar investment tax credit (ITC) is another key federal policy mechanism established in 2005 to motivate the deployment of renewable electricity projects in the USA. Even though limited supply is seen as a disadvantage, a credit of 30% of qualified expenditures for systems that are installed in a household can be claimed by taxpayers. Another key scheme is renewable energy certificates (RECs) that are designed instrument to track, account, and assign ownership to renewable energy generation and help enhance the development of renewable energy projects based on a market status. Generally, REC is issued when an operator successfully delivers 1 MWh of electricity generated from RES to the power grid [15]. The virtual net metering (VNM) tool, which is nearly identical in structure to the standard net metering (SNM), was introduced under the California Solar Initiative Multifamily Affordable Solar Housing Program (MASH) as a means of enabling low-income families who are living in apartment complexes to make benefits by receiving credits from the solar system owner (building owner) without being required as low-income tenants to physically connecting their meters to the solar system [16].

In addition to the mechanisms and policies mentioned above, the USA has been providing financial support in different forms which induced a tremendous growth of integrating PV systems in the dwellings. Programs such as offering repayment-guaranteed loans or direct lending of money to energy market participants had a

Table 17.3 A summary of actions taken by the government in the USA

Country	Total PV installed capacity (MW)	Appropriate actions taken by government	Inappropriate actions taken by government
USA	25.620	Federal tax credit	10-year long-term contracts increased insecurity and risk for the generators
		Loan and insurance programs	Overreporting weak control
		RPS accessible via the internet	Ambiguity of contract terms to customers

positive impact on expanding the use of solar energy systems. These subsidized loans helped householder with low income to afford the cost of solar system [17]. Table 17.3 illustrates the key actions that influenced the introduction of solar energy in the USA.

17.4.4 The UK

In aiming to reduce GHG emissions and coping with depletion of the country's natural resources, the UK outlined numerous commitments including several incentives to expand the use of renewable energy. The primary energy production cost (10% of the UK's gross domestic product (GDP)) is much higher than most of the other industrialized countries, which put more pressure on the UK to seek other alternatives. In the UK, electricity is generated in many forms. According to 2015 statistics, fossil fuel is the most used source to produce electricity. Natural gas (29.5%) and coal (22%) are the main sources of energy. Other sources, such as nuclear (20.8%) and renewables (27.7%), are major players in the UK's energy mix. Currently, oil contribution is under 1%. The depletion of its domestic fossil fuel reserves combined with projected growth in global demand urges the UK government to implement plenty of reforming schemes to include renewable sources as a key part of its energy mix [18].

Several incentive schemes have been launched in the last decade to stimulate investments of renewable energy for both individuals and business. For instance, Renewable Obligation (RO) was introduced in 2002 to place an obligation on electricity suppliers to receive an increasing share of their electricity from renewable sources. Operators carry out this by purchasing a Renewable Obligation Certificate (ROC) which is issued to all accredited generators for the share of the generated renewable electricity. Therefore, two sources of revenue are available to the generators: earnings from the sale of the ROCs and revenue from selling generated electricity to the wholesale market, regardless of the electricity sourced from renewable or nonrenewable energy. The system of ROC was modified to ensure that all types of renewables are receiving the appropriate support without bias toward a particular technology. Therefore, since 2009, the government has banded issuing one ROC for each MWh generated from renewables as an attempt to create

Table 17.4 A summary of actions taken by the government in the UK

Country	Total PV installed capacity (MW)	Appropriate actions taken by government	Inappropriate actions taken by government
UK	8.780	Transition from tendering to quota system	Ambiguity of the number of projects the government intended to open for bidding has increased the risk for developers and investors
		Offer providers with secure long-time contract and finance	Absence of future guarantees increased the risk for investors
		Charging tax on all fossil fuels	Failure to provide a framework for stakeholders
		Obligation forced retailers to buy renewable energy certificate which helps to create a new renewable market	The 5-year Non-Fossil Fuel Obligation contract offered for winners was too long
			Awarding projects to the lowest bidders negatively affected the industry

balance and prevent market distortions [19]. Regarding energy efficiency-related tools, the Green Deal is one of the vital financing mechanisms that enables householders and business to gain profits based on pay-as-you-save policy. It encourages householders and business owners to install energy efficiency measures at no upfront cost and allow the payment to be made through their electricity bills. To become eligible of receiving finance for energy measures, the saving must be greater or equal to the amount of the electricity bill. This policy came into force on January 2013 [20].

Another instrument is the Non-Fossil Fuel Obligation (NFFO) which mandates the former public electricity suppliers (PES) to purchase electricity from renewable generators. In fact, NFFO was introduced before the RO scheme introduction. It was the government's primary instrument of renewable energy policy. Currently NFFO is no longer available to new generators; however, existing contracts are valid until the expiration of the last contract in 2019 [21].

Table 17.4 summarizes the most significant policies that have positively or negatively affected the introduction of solar energy in the UK.

17.4.5 Spain

Regardless of its limited hydrocarbon resources, Spain has successfully built a diverse and reliable power generation system after several years of efforts. The primary energy consumed in Spain is fossil fuel. Oil represents the dominant share of 42.3% followed by natural gas at 19.8% and coal at 11.6%. Nuclear is accounted up to 12% while renewable energy sourcing 14.3% of the total energy consumed [22].

To ensure a reliable and sustainable electricity supply, a great effort has been made to tackle the imbalance between the costs and revenues of the electricity generated from renewable resources. These reforms have a fundamental impact on improving the remuneration schemes facilitating access for a green economy. One step that significantly has an impact on the renewable energy development in Spain is the merge of the civil society organizations and the independent developers as key advocate groups. Their support which was in line with the government's plan gave a boost to renewable energy projects around the country [23].

In the mid-2000s, Spain introduced market premium and FiT incentive programs with very generous rates of remuneration schemes. This resulted in the most significant capacity ever installed in such a short time, making the Spanish solar power market in 2008 the largest market in the world. However, the government started to gradually reduce the uptake rates and financial incentives as a response to the economic challenges that the country countered. The dramatic increase in the renewable energy installed capacity has posed a risk and distorted the electricity market. This urged Spain to suspend both market premium and FiT at the beginning of 2012 and to become the first European country taking this action. It has been reported that the retroactive cuts to market premium and FiT incentives made by the government have posed a significant degree of risk that may negatively affect future investments in renewable energy projects [24].

RE incentives gave the project operators and developers who possess a capacity of 100 MW or less two options to choose from:

- To receive market premium incentives without an electricity purchase obligation.
- To receive FiT incentives including a purchase obligation.

At the early stages of the FiT implementation, solar PV projects were guaranteed with a fixed rate for the first 25 years of the solar generating facility. However, for the reasons mentioned above, this fixed rate was reduced thereafter. In 2004, all solar PV projects which have a capacity less than 100 kW could receive a fixed tariff equal to 575% of the reference price, while projects with a capacity larger than 100 kW could receive a fixed tariff equal to 300% of the reference price. At that time, tariffs dedicated to PV generating facilities were receiving €0.40/kWh and €0.21/kWh, respectively. In 2008, FiT tariffs were modified and restructured to allocate additional incentives for rooftop solar PV systems (€0.34/kWh) and ground-mounted systems (€0.32/kWh) [24].

Regardless of all measurements that have been taken to readjust electricity rates, many users continued to pay rates that are in fact less than the cost of the all-in electricity, which resulted in an accumulating tariff deficit among Spanish utility companies. Additionally, qualified renewable generating facilities which were receiving tariffs and market premiums that were higher than the market tariffs have also contributed to the tariff deficit [25]. Even though financial subsidies are no longer available to new solar PV projects, it is a widely held view that solar PV systems will continue to be adopted in the future yet on a slower base [25]. Table 17.5 summarizes the Spanish government's actions toward the implementation of solar energy.

Table 17.5 A summary of actions taken by the government in Spain

Country	Total PV installed capacity (MW)	Appropriate actions taken by government	Inappropriate actions taken by government
Spain	5.400	Capacity of less than 100 MW sell to distributors and distributors buy it at fixed rate	Low policy change caused an unwanted increase
		Guaranteed grid access for solar energy resources	Poor coordination between regional and national authorities
		Reducing lifetime of FiT payment to 25 years	Support level is revised only every 4 years
		Provide generators with 2 options; a fixed feed-in rate adjusted annually or a fixed-premium rate on top of the electricity market	Complex administrative procedures and variation of regional procedures
			Government allowed PV system to connect to low-voltage grid, while most generators have a medium-voltage grid connection

17.4.6 India

In recent years, India put much effort into reshaping its economy and improving the average income rate of its citizens. It has already made notable progress at different levels. In conjunction with this development, India's energy sector has grown tremendously along with the economic and population growth [26]. India noticed the sense of urgency to develop new alternative energy sources and started to shift to a more diversified energy structure by offering a set of incentive programs. For instance, solar power has received plenty of financial incentives from the central and state governments of India which resulted in a significant deployment of solar power across the country. Most of these efforts are dedicated to remote areas or areas that have electricity supply shortages. India has established the Indian Renewable Energy Development Agency acting under the Ministry of New and Renewable Energy (MNRE) where most of initiatives dedicated to renewable energy technologies are initiated and managed [27]. As a means of catalyzing renewable projects, a 10-year tax deduction was offered to all project developers who are engaged in power generation and/or distribution activities assuming that they would begin before 31 March 2014. Based on its income, renewable generating facilities are obliged to pay a tax equal to 20–21% as a minimum alternative that would be offset thereafter [27].

India has also focused on attracting foreign direct investment (FDI); the government has introduced the generation-based incentive (GBI) schemes as a means of supporting renewable projects under independent power producers (IPP). This initiative was designed for wind and solar power projects offering them accelerated depreciation. However, it was later found that FDI and IIPs were not applicable for the

Table 17.6 A summary of actions taken by the government in India

Country	Total PV installed capacity (MW)	Appropriate actions taken by government	Inappropriate actions taken by government
India	5.050	Establish independent ministry for nonconventional energy sources	Inadequate training and maintenance of the technology
		Introduction of RECs	Not developing adequate strategies to control the improper use of electricity by end users
		Encourage private investments in solar energy	
			Imbalance of tariff structures

depreciation provisions. The GBI tariffs for solar and wind energy projects which are fixed by the state regulatory commissions are available for all projects with a capacity up to 4000 MW and projects set up before March 2012 [27]. Several other measures such as RECs and renewable purchase obligation (RPO) were introduced by the National Action Plan on Climate Change (NAPCC) to promote renewable projects to meet the set targets of 10% by 2015 and 15% by 2020 at the national level.

RPO scheme obliges open-access consumers and distribution companies to purchase a certain share of their consumed energy from renewable energy resources. The RECs' market started in 2011 to meet the RPO goals. However, procedures are being considered for modifying its provisions. Despite the criticism the RECs' mechanism receives for not being adequately supported yet, it is thought that the enforcement of RPO will help in securing the capacity needed for the RECs' market [27]. Table 17.6 presents the most influential policies made by the government in India in effort to catalyze the development of solar energy.

17.4.7 Greece

Some significant reforms have been implemented in Greece aiming for energy efficiency improvement and further liberalization of the energy sector. It has been working with its neighboring countries to improve the integration of RES in the electricity market and to allegiance with prerequisites of EU state aid regulations. Greece has adopted ambitious goals and measures for developing the solar energy sector. The primary goal is to increase the contribution of RE in gross total final consumption by up to 20% by 2020. This number is triple the 7% share in 2005 and 2% higher than its EU obligation [28]. The system operators are obliged by law to offtake electricity generated at fixed prices. Priority dispatch of renewable energy is given by the system operator based on the grid code and other relevant standards offering 20-year power purchase agreements (PPAs). Renewable energy project developers, requesting to connect to the electricity grid, are obliged to agree on the PPA provision [28].

Table 17.7 A summary of actions taken by the government in Greece

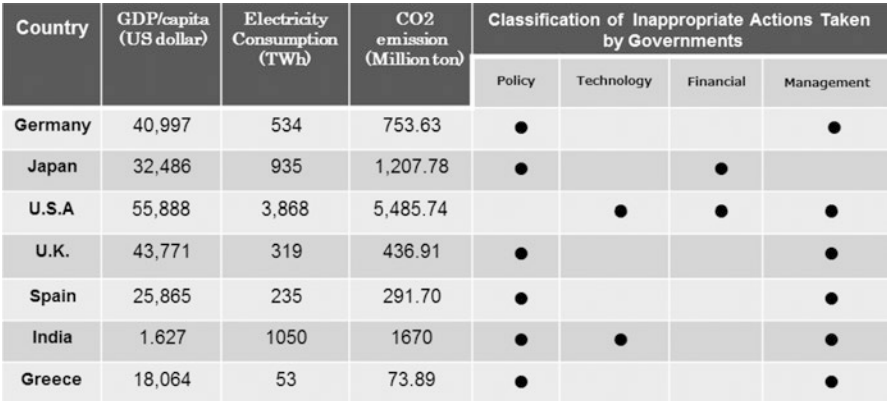
ountry	Total PV installed capacity (MW)	Appropriate actions taken by government	Inappropriate actions taken by government
Greece	2.523	Encourage technological and industrial research	Unprofessional response to opposing residents caused termination of some renewable energy projects
		Established a third-party financing scheme (pay not for the installation but the manufacture at a fixed monthly rate)	Long and complicated procedure directly affected the period of obtaining production and operation licenses
		Tax deduction of system cost	
		Modified building code	

In Greece, there are two categories of FiT's available renewable generating facilities: a FiT limited to solar PV installers and a FiT for non-solar PV renewable energy sources. Only the former is reviewed in this paper. FiT for solar PV installation came into force 2009 with separate tariffs for all other RE projects. Over time, fixed tariffs were gradually reduced. Tariffs for PV projects with an installed capacity of more than 100 kW located within the interconnected system, i.e., mainland Greece, were reduced to €292.08/MWh. Moreover, tariffs for projects with an installed capacity of less than 100 kW were reduced to €328.60/MWh. On the other hand, other PV projects located out of the interconnected system are qualified to receive a tariff of €328.60/MWh with no limit of installed capacity. The government has also approved virtual net metering for specific investors, which enabled parties such as schools, universities, city and regional councils, and farmers to develop solar PV in places other than of the actual power consumption [28, 29]. In 2013, the government set new retroactive measures to control the RES fund deficit issue caused by over-installment. The so-called new deal is included in a package of measures that oblige operating PV projects to accept feed-in-tariff cuts in exchange for extending the producers' bank loan duration and reducing their loan rates. It is thought that solar PV producers will be required to accept minimum FiT cuts of 25% for their operational assets. Moreover, it is also expected that specific details of each solar project such as loan conditions and building cost will be also taken into consideration and verified separately [28]. In Table 17.7, a summary of the most significant actions made by the government of Greece is presented.

17.5 Summary

This paper aimed at summarizing seven selected countries' experiences in promoting solar power as an essential energy source in their energy mix. Whether it is political, technological, economic, or social, each one of these countries has faced

Table 17.8 Classification of inappropriate actions taken by governments



Country	GDP/capita (US dollar)	Electricity Consumption (TWh)	CO2 emission (Million ton)	Classification of Inappropriate Actions Taken by Governments			
				Policy	Technology	Financial	Management
Germany	40,997	534	753.63	●			●
Japan	32,486	935	1,207.78	●		●	
U.S.A	55,888	3,868	5,485.74		●	●	●
U.K.	43,771	319	436.91	●			●
Spain	25,865	235	291.70	●			●
India	1.627	1050	1670	●	●		●
Greece	18,064	53	73.89	●			●

several challenges and tackled them with different risks to create a new market for this new source of power. Most actions that positively or negatively affected the efforts of solar power deployment in each country are summarized. Moreover, as shown in Table 17.8, shortcomings in each phase are analyzed and then classified based on category.

The technological and financial aspects are significant, as they play an essential part in this equation and must not be overlooked. However, as can be clearly seen in the table above, legislative (i.e., policy) and administrative (i.e., management) aspects are crucial, if not even more crucial to the successful integration of the solar energy capacity. It can be said that we have reached a certain level that technological issues are no longer the biggest challenge. Designing an optimal combination of all these areas will lead to a steady transition toward sustainable energy supply by utilizing this technology.

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Chapter 18
Solar Photovoltaic Market Adoption: Dilemma of Technological Exploitation vs Technological Exploration

Ranaporn Tantiwechwuttikul, Masaru Yarime, and Kohzo Ito

18.1 Introduction

Solar photovoltaic (PV) technology has been developing since the 1960s, and a series of technological breakthroughs have been achieved. Yet, the market adoption is still very reticent and concentrated particularly on the silicon-based PV. The barriers of PV deployment typically revolve around the issues of technological challenges and non-technological aspects, namely, the policy and economics. Oftentimes, the in-depth—yet disintegrated—analysis was conducted by experts in the respective fields to highlight some issues and concerns. But the lack of all-encompassing perspective is where this paper aimed to fulfil.

Though a market of PV modules is highly dynamic and global one engaging market players from all over the world, initial policy-induced market growth in Europe in the 1990s promoted not only mass-production industry but also process innovation particularly in Asia. Currently, Asia accounts for about 85% of the global PV module manufacturing capacity. In addition, this region has the highest PV market growth.

A comparative review—from archives, field observations, and informant interviews—in four countries (China, Malaysia, Thailand, and India) is executed to identify relationships and emerging themes. The policy shifting is amongst outstanding

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themes in which government largely changes from *governance by rules* to *governance by goals*, and private sector plays an increasing important role in PV market. In terms of PV system installation, current segmentation is over-dominated by utility-scale PV system, while the PV policy trend shifts towards the distributed system (e.g., rooftop, self-consumption, off-grid/stand-alone system).

In addition, a methodological framework of sectoral systems of innovation [1, 2] reveals structure and interactions embedded in PV sector. Three elements of knowledge and technological domains, actors and networks, and institutions are identified and examined due to the uniqueness in each element's characteristics and set of dynamics embedded in different national settings.

18.2 Review of PV Policy

18.2.1 China

Due to rapid economic growth since the 1990s, Chinese energy consumption, together with carbon emissions, has drastically increased. In order to meet the growing energy demand and mitigate carbon emissions, clean manufacturing and renewable energy technology are essential elements for further development. Like other developing countries, China has benefited from technology leapfrogging and technology transfer. Initially, off-grid PV system was used for rural electrification. But the export-oriented industrial strategy in the 2000s set China apart as the world leader of PV manufacturing which also intensified PV price competition globally. The global financial crisis during 2007–2009 and trade dispute between China and its major export countries slowed down PV installation; thus national policy shifted towards domestic deployment to absorb oversupply of Chinese PV module. Hence, domestic PV installation capacity has been rapidly increased since 2010, and by the end of 2015, China overtook Germany and became the world's largest country of PV cumulative installed capacity (43 GWp) [3]. A continuing PV market growth marked a total of 78 GWp by the end of 2016 [4].

Chinese PV policy landscapes were driven by the pursuit of economic gain through export and enhancing technological capacity, prior to installing the domestic deployment support [5]. Yet, notable market policies since 2009 included Golden Sun programme (2009–2011), building-integrated photovoltaics (BIPV) and BIPV demonstration project, concession bidding FiT for large-scale on-grid PV projects, and regional deployment support policies.

Investment incentive programmes can be categorised into three groups:

1. Ministry of Science and Technology (MOST) innovation fund for small technology-based firms.

2. Regional investment support policies, e.g., refund policies to promote new plant investment.
3. Loan and credit facilities provided by government/state for manufacturers.

R&D supports through various means:

1. MOST budget for research institutions and firms in accordance with the federal government's '5-year plan' basic scientific research is included.
2. National Development and Reform Commission (NDRC) programme targeted market-oriented R&D development and demonstration projects.
3. Exemption of import tax and VAT for R&D institutions with minimum full-time R&D employee requirement.
4. Regional R&D support policies, e.g. subsidy for senior technical employees in PV manufacturer.

PV supply chain in China demonstrated rapid technological learning supported by indigenous R&D expenditure from both central and regional governments during 1996–2008. The initial step relied much on the foreign technology acquisition, so that module production lines could be established. Then cumulative in-house and joint R&D paved the way to upstream activities of higher profit margin from silicon and ingot/wafer productions which was reflected by the higher global share of Chinese patent applications [6]. The technology catching up gained momentum in the early 2000s and strengthened Chinese's PV manufacturing position in global market.

The evolution of Chinese PV policy can be clustered into four phases having specific policy design changes as in Table 18.1 [7].

Table 18.1 Chinese PV policy evolution

	Changes in policy design
Phase I 1980–2002	*Rural electrification and technology transfer* – National Basic Research Program – Market incentives for renewable energy adoption/pilot programme
Phase II 2003–2008	*Export-oriented industrial strategy* – Solar PV industry as Chinese high-technology products for export – Medium- and long-term development plan for RE – International cooperation program – In-house R&D
Phase III 2009–2011	*Continued industry support and beginning of domestic deployment* – Renewable energy sector promotion as a core strategic industry – Financial incentive, e.g. renewable electricity surcharge, rooftop subsidy program, nationwide feed-in tariff – Large demonstration programme
Phase IV 2012–present	*Increase domestic installed capacity and infrastructure development* – Extended market support – Distributed solar power generation on-grid service agreement

18.2.2 Malaysia

While China and Taiwan gain low-cost leadership position from scale of production and process innovation, other Asian countries chose different strategies to increase their production capacities. Malaysia, in particular, initially established partnerships with a few technology-advanced multinational players as production hubs taking advantages not only from its geographical location, political stability, reliable infrastructure, elastic supply of low-cost labour and attractive incentives, but also the well-established semiconductor industry [8]. Later on, many Chinese solar companies expanded their productions in other Southeast Asian countries, especially Malaysia, due to the anti-dumping duties and countervailing investigations from the USA and EU [9]. The share of Malaysia's PV production has been increasing significantly since 2009 [10].

However, PV technology deployment in Malaysia remains marginal compared with fossil fuels in terms of the total electricity production. But the grid-connected PV installation capacity has been increasing significantly since 2006 due to the Malaysian Building Integrated Photovoltaic (MBIPV) project during 2006–2010 which achieved 1516 MW installation in 109 buildings. Furthermore, the recent incline in PV installation capacity from 137.51 MWp in 2013 to 321.95 MWp in 2016 is due to the feed-in tariff implemented since 2011, and currently (March 2017) solar PV notably shares 64.7% of the total RE installation capacity. The major policy development in three phases is shown in Table 18.2 [11, 12].

As part of Malaysia's National Transformation Programme, the Economic Transformation Programme (ETP)—launched in 2010 and aimed to transform Malaysia into a high-income nation by 2020—has become the major policy-driving force. Embedded within 12 National Key Economic Areas (NKEAs), at least 3 entry point projects (EPPs) are related to PV industry: (1) building up renewable energy and solar power capacity, (2) increasing solar module producers, and (3) development of balance of systems for solar photovoltaics [13].

Investment incentive programmes included the following:

Table 18.2 Malaysian PV policy evolution

	Changes in policy design
Phase I Prior 2006	*Rural electrification* – Off-grid PV installation funded by government
Phase II 2006–2010	*Grid-connected PV systems on buildings (residential and commercial)* – Reducing long-term cost of building-integrated PV – Small Renewable Energy Power (SREP) programme was enhanced to include PV
Phase III 2010–present	*Domestic capacity development in high value-added segments of the global value chain* – Moving up the value chain to niche R&D – Absorbing value added in downstream application, e.g. local PV market simulation using feed-in tariff as key policy driver, and other financial supports

1. Government incentives through FiT and investment tax allowance.
2. Commercial bank activities offer green technology financing scheme.
3. Sustainable building requirements provide the green building index (GBI) rating tool.

R&D supports are mainly provided by government entities through Ministry of Science, Technology and Innovation addressing on the green technology research. Most of the research is carried out by the research universities in Malaysia.

From global perspective, Malaysia is still far behind Germany and China in terms of PV manufacturing and domestic installation capacity. But from regional perspective, Malaysia is very active amongst other Southeast Asian countries. The nation's transformation goal and action plan have been implemented, and progresses are monitored attentively addressing both supply- and demand-side policy supports. Outstandingly, capacity developments in upstream and downstream of manufacturing, together with the synergy across PV chain, are highly valued and prioritised in national agenda.

18.2.3 Thailand

In Southeast Asian region, Thailand is by far the most active country in terms of cumulative PV installation capacity. Owning very much to its electricity supply industry reformation after the Asian financial crisis in 1997, Thailand's electric sector has been extended from government monopoly to market liberalisation which is then accommodated the proliferation of RE projects. Despite generous incentive from Adder programme since 2007, solar PV projects bloomed from 2008 when global PV module price reduced significantly. Then a series of policy modifications was implemented to incorporate the rapid changes from both domestic market and global phenomenon. The evolution of Thailand PV policy can be clustered into four phases having specific policy design changes as shown in Table 18.3 [14].

In contrast to Malaysia, Thailand PV policy landscapes were designed chiefly for technological exploitation and less emphasised on R&D. Hence, the country extremely relied on PV technology imports. Besides Adder and FiT programmes, other investment incentive programmes are:

1. Investment grant: for import duty exemptions on equipment and machinery and corporate income tax exemption for the selling of energy. Grants can be categorised into three groups for PV projects with power purchase agreement, PV supply chain industry, and PV auxiliary devices, e.g. battery inverter.
2. ESCO Revolving Fund: provides lower-risk capital, equity investment through ESCO venture capital, equipment leasing, and credit guarantee. This 300 million THB fund is sponsored by DEDE, under the financial support from Energy Conservation Promotion Fund (ENCON Fund) and managed by Energy for Environment Foundation [15].

Table 18.3 Thai PV policy evolution

	Changes in policy design
Phase I 1985–2006	*Rural electrification and electric sector privatisation* – Solar PV demonstration project in rural areas – Encouragement on private power generations
Phase II 2007–2010	*Renewable energy development plan and strategy* – Endorsed long-term national energy plan – Introducing Adder programme (feed-in premium)
Phase III 2011–2014	*Revision of RE plan and target, with highlight on rooftop PV* – Adjusted RE plan and target with market conditions – Introducing feed-in tariff programme
Phase IV 2015–present	*Alignment of all energy plans and start of PV self-consumption* – Starting a pilot project on grid-tied self-consumption system – Considering alternative mechanisms to promote RE (e.g. net billing, net metering)

R&D supports on PV research are not made explicit and typically included as part of broader research topics. Four PV research themes are PV materials, inverter for both grid-connected and off-grid system, demonstration and evaluation, and policy and regulation.

Concerning PV supply chain, there were only five PV manufacturing companies in 2014 with a combined installation capacity of 234 MW. In 2015, seven new manufacturing companies (mainly Chinese and Taiwanese firms) having 3634 MW installation capacity were registered. Similar trends occurred for inverter market. Initially there was only one domestic inverter manufacturing company, but in 2015 another manufacturing company was established together with the new 36 inverter-imported companies [16].

Thailand PV industry's prospects and challenges can be classified into three key areas: firstly, the expertise in the engineering, procurement, and construction (EPC) and the operation and maintenance (O&M) services thanks to the rapid PV system installation domestically and many firms begin to expand their business footprint in neighbouring countries; secondly, the testing and validation centres for PV products and service due to the suitable geographical location and climate; and lastly, the development of specific PV technologies for high-temperature regions [17].

18.2.4 India

India is the world's third largest market in terms of power generated, but the country still struggles with two major issues: deficit electricity supply and huge losses in transmission and distribution (T&D) network. In 2014, electric power coverage was estimated at 79.2% of the total 1.3 billion population; thus more than 270 million people had no access to electricity. In addition, T&D losses were reported at 19% of electricity output. The high rates were largely caused by illegal usage, i.e., bypassing or tampering with the metre or bribing utility metre readers

Table 18.4 Indian PV policy evolution

	Changes in policy design
Phase I 1998–2004	*Electric sector liberalisation* – Diverted from state-owned power generations; allowed 100% foreign investment in power sector
Phase II 2005–2009	*Ultra Mega Power Projects (UMPPs)* – Fast-track expansion of power capacity – Coal-based plants with over 4000 MW capacity awarded through competitive tariff-based tender procedures – From 16 targeted UMPPs, 4 were awarded, and only 1 was commissioned in 2012
Phase III 2010–present	*Vision of PV plan and target* – Introduced the Jawaharlal Nehru National Solar Mission (JNNSM) in January 2010 targeting 20 GWp grid-connected PV and 2 GW off-grid capacity by 2022 – Revised grid-connected PV target from 20 GWp to 100 GWp in 2015 – Planned for solar parks and Ultra Mega Solar Power Projects from 2014

or billing agents, as well as inadequate infrastructure. These two issues set India apart from other four selected countries which had 100% access to electricity and no more than 6% T&D losses [18]. The lack of grid-connected facilities, however, emphasised the benefits from distributed and off-grid generation, particularly from renewable energy resources. Astonishingly, India PV market growth has been soaring from a cumulative PV installation capacity (grid-connected system) of 39.66 MWp in 2011 [19] to 9010 MWp in 2016 [4] and to 12288.83 MWp by the end of April 2017 [20]. Regarding PV development in India, policy landscape has been transformed significantly since 2010 as described in Table 18.4.

Key drivers for rapid Indian PV development are the proactive solar policy framing and implementation across 16 states aiming for clean energy adoption and industrial development. JNNSM policy impacts can be reflected by solar PV trade statistics; the abrupt PV demand in 2011–2012 (1348.48 million USD) was more than quintuple of the total import volume in 2010–2011 (252.63 million USD), and market demand is growing steadily [21].

Investment incentive programmes included:

1. Government incentives for large-scale solar power plants and grid-connected rooftop solar.
2. State government incentives provide partial financial assistance for solar city initiatives.
3. National Clean Energy Funds from the multi-government agencies (i.e., government departments, government institutions, commercial banks, railways) for installation of gird-connected rooftop solar PV systems.

R&D supports through government are made through its institution funding (i.e., Department of Science and Technology, Department of Industrial Research, Ministry of New & Renewable Energy) for research activities in renewable sector including solar PV.

18.3 Comparative Analysis

German feed-in tariff (FiT) programme triggered an unprecedented phase of market expansion and enabled mobilisation of private investment for PV production and installation far beyond its national boundary. Initially, Germans gain competitive advantages as the first technological mover, which then supported the build-up of domestic PV industry during the 1990s–2003. Subsequently, China adopted PV technological diffusion particularly in PV manufacturing. These transnational linkages could not solely be explained by the lead-lag market model – a linear concept of the internationalisation of demand driving the internationalisation of supply. Instead, many studies on PV technological innovation systems between these two countries have revealed empirical data of co-evolved and reinforced patterns through indirect spillovers and feedback mechanism of knowledge and technology domain [5, 22, 23].

Demonstration effect is another key driver in two regards: PV deployment (from Germany to global market) and PV production (from low-cost production in China to niche R&D in Malaysia). While the product innovation tends to be originated from Western countries where R&D activities are strongly asserted, the process innovation is impressively generated from the developing countries along the manufacturing process, installation, and operation. Germany still holds a strong position in inverters and PV-related equipment, where profit share is relatively high. Pursuing cost-competitive advantages, China (including Taiwan) places strong R&D activities in upstream supply chain which consequently results in the drastic decline of PV module cost globally during 2004–2008.

Albeit other factors, Chinese trade dispute with major importer countries and the global financial crisis during 2007–2009 had shrunk the global PV demand. Counter-mechanisms from both international firms and government decisions lead to two phenomena: the expansion of PV manufacturing firms outside China and the Chinese PV domestic market adoption. From this viewpoint, the role of institutions is truly critical not only the rate of technological change but also the organisation of innovation activity and performance. The deliberate and well-planned decisions especially in China and Malaysia affirm the active national policies' influences. Despite a marginal domestic PV installation, Malaysia adopts FiT based on the polluter payer schemes and renewable portfolio standards (RPS) to facilitate RE growth, alongside with strategic R&D aiming to move up PV value chain. Nevertheless, the unpredicted consequence of actors' interaction demands the improvising strategies and quick policy responses from national institutions. Cases of Thailand and India clearly addressed this issue.

Three categories of policy design help clarify different aspects concerning PV diffusion in government agenda [24]:

1. *Market-based support mechanism* can be classified into two subcategories:
   (a) Price-based market instruments—price is determined by the policymaker, whereas quantity is regulated by the market. In addition to price, the policy can be investment-focused (i.e. investment subsidies, tax incentives) and generation-focused (i.e., FiT, net metering).

(b) Quantity-based market instruments—quantity is determined by the policy-maker, whereas price is determined by the market. Quota obligation (tradable green certificates/renewable portfolio standards), tender scheme, and auctions are amongst policy choices.

2. *Regulatory policy*: grid connection capacity, administrative procedures, and technical standards are amongst policy options aiming for RE project establishment and streamline project execution.
3. *Flanking policy* includes, but not limited to, R&D grants/fundings, education and training programmes, and soft loans.

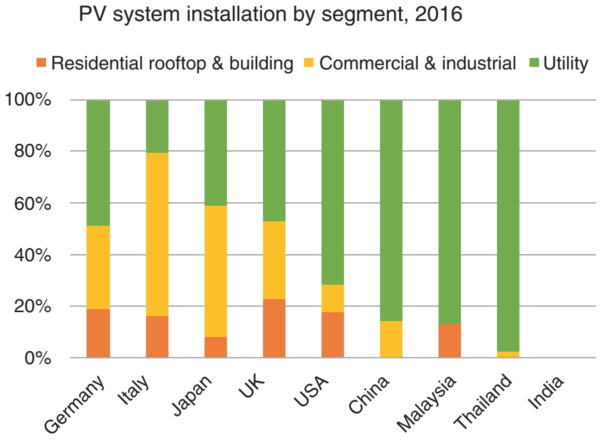
Despite different degrees of PV policy deployment, clearly all four countries adopt and promote market-based support mechanisms. However, regulatory and flanking policies are substantially important and need more attention.

Considering actors and networks in PV industry, apart from typical firms and non-firm organisations directly involved with PV market (e.g., utilities, equipment suppliers, academia, and financing entities), the regional and national PV targets promote the goal-driven strategies and accelerate the implementation as witnessed across EU and ASEAN countries. Furthermore, international and regional collaboration foster knowledge transfer through investment (e.g., Asia Development Bank-funded PV projects, UN Green Climate Fund) and educational programmes (e.g., RENAC, Renewables Academy based in Germany providing training courses via online, summer schools, and outreach projects particularly for developing countries; PV technology focus is applied to India, the Philippines, and Thailand).

Based on case study approach, four countries are selected based on theoretical sampling aiming to draw attentions to specific issues. Besides the cross-country interdependencies and influences of PV global market and dynamics, the environmental variation embedded within each national setting also provides or highlights uncommon occurrences. The analysis of PV installation pattern based on how PV systems have been installed as rooftop, building, or ground-mounted systems can, to some extent, reflect segmentation of PV market broadly classified as residential, commercial/industrial, and utility-scale projects. Based on the most recent available database and each country's classification, Fig. 18.1 displays PV system installation pattern (grid-connected) in four selected countries along with other top five countries. Applying country-income criteria [3], three groupings are the high-income countries (Germany, Italy, Japan, the UK, and the USA), the upper middle-income countries (China, Malaysia, and Thailand), and the lower middle-income country (India). Unfortunately, no data of PV system size installation in India is available; given that India is selected as a case study based on its lack of grid infrastructure, thus a lack of detailed grid-connected database has been anticipated in advance.

Segmentation addresses not only the direct impacts from PV policy on technological diffusion but also other technical challenges. PV ground-mounted system typically infers as a utility-scale project which intrinsically requires a large area of land use and availability of grid-connected capacity. Some ground-mounted system may incorporate tracking devices to enhance energy yield. Ground-mounted system can also be deployed as microgrid management or community electrification. PV

Fig. 18.1 PV system installation by segment in selected countries, by end of 2016



Note: Own compilation and classification

rooftop and building-integrated PV (BIPV), on the other hand, can utilise the existing available space but may trade off with energy yield depending on the orientation and inclination (tilt) of PV modules installed on the fixed roof or façade. Both rooftop and BIPV can be deployed as grid-tied (sell electricity to the grid) or self-consumption. Despite variation of the absolute number of cumulative installed capacity in each country, the governments in developed countries put strong emphasis on rooftop and BIPV systems in their policy design, whereas the developing countries' PV policy tends to be in favour of utility-scale projects—which are easier to manage and integrate into an existing centralised electricity grid system.

18.4 Conditions for Catch-Up

18.4.1 Underpinning Theories

Amongst economic growth theories, economic convergence model is proposed by Robert Solow. He assumed that capital has diminishing returns; thus, the additional capital for accessing the same technology in poor countries will increase output compared to that in rich countries. However, Solow's assumptions are not always satisfied. In part, the knowledge accessibility and technology availability do not necessary lead to technological utilisation. And a lack of capital flow to poor countries is another issue. The basic convergence prediction by the Solow model is yet to be proved for broader context. Realistically analysing the effects of technological change, the endogenous growth theory developed by Paul Romer and Robert Luca suggests that growth is primarily the result of internal factors. Hence, the result may be divergence between countries rather than convergence [25].

Therefore, a concept of catch-up is more precise and applicable in this research context. Catch-up relates to the ability of a single country to narrow the gap in productivity and income vis-à-vis a leader country. Preliminary classification of catch-up strategies is by Thorstein Veblen and Alexander Gerschenkron. Veblen argued that the conditions for industrialisation in latecomer economics are due solely to technological changes; so, technological availability is of the essence. By contrast, Gerschenkron perceived much complex systems including changes in physical, financial, and institutional infrastructure. Institutional instruments are of the essence aiming to mobilise resources required to undertake necessary changes [26]. So far the research findings support the latter viewpoint, and the institutional instruments can perhaps decompose into four subsystems of economic, energy infrastructure, policy, and technology. Policy and technology are accentuated in this paper.

18.4.2 Policy Implications

Institutional instruments are crucial to provide a prerequisite for PV technological exploitation and exploration. The core of policy design should envision a balance perspective, but whether the execution is simultaneous or sequential is subject to national settings, market conditions, and capability. Either exploitation or exploration, conditions for catch-up will be more stringent over time from not only the current and near-future global and domestic market factors but also other technology discontinuities and disruptions. Thus, policy should be designed systemically, rather than compartmentally.

PV technological exploitation is unique because a rapid cost reduction greatly rewards the late technological adopters. On the flip side, PV projects can be intentionally delayed taking this cost advantage. Since the cost reduction embedded in PV model is marginal compared to cost reduction in the balance of system, the benefits from PV project realisation should surplus PV cost saving. In addition, greater demands on technological capability are in line to other radical technological changes and improvement (e.g., ICT, weather forecasts, energy storage technologies) which help optimise and/or enhance PV system. Therefore, technological exploitation should be considered from a collective manner of PV industry and related technologies, and the benefits include both direct and indirect.

PV technological exploration can take advantage from the triple helix of university-industry-government interactions. To pursue knowledge-based societies, many routes are possible, namely, the statist model where government is the dominant institutional sphere, the laissez-faire model where each institutional sphere is clearly separated, and the field interaction model of helices with an internal core and external field space of each entity. University technology transfer capabilities can be made from research group, liaison office, technology transfer office, and incubator [27].

18.5 Summary

Policy-induced technological change plays a crucial role in PV industry through National Strategic Development Plan, institutional establishment and arrangement, and firm product and process innovations. But the knowledge and technological domains are often left behind, particularly in developing countries. Therefore, the PV policy needs a systematic, not a compartmental, perspective and the balance of policy in technological exploitation and exploration with a timely policy adaptation. Furthermore, the systems approach analysis extends a discussion on PV industry development from focusing merely PV supply chain to involving collectively PV-related industries. Each nation requires to create the political and economic conditions for establishing a robust, multi-faceted policy to anticipate and accommodate such technological transition not only for the purpose of short-term technological catch-up but also for the long-term technological competitiveness through a vision of the knowledge-based society.

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Chapter 19
Energy System Design Incorporating Socio-Technical Regimes and Sustainability in Japan: Energy Use, Knowledge, and Choice in a Liberalizing Energy Market

Andrew John Chapman and Nugroho Agung Pambudi

19.1 Introduction

Japan is reliant on foreign energy imports to meet their overall energy demands and has a very low level of energy security [1]. As a result, the reduction of greenhouse gas (GHG) emissions, through an increased deployment of renewable energy (RE), has become a central pillar of the Japanese energy policy approach toward addressing energy security, economic efficiency, environmental awareness, and safety (known as 3E+S) [2]. As concrete medium-term measures, the Japanese government intends to increase RE generation levels to 22–24% of total power generation and to reduce GHG emissions by 26% (relative to 2013 levels) by 2030 [1, 3]. The long-term (2050) goal for Japan is to reduce GHG levels by 80%. These are ambitious goals, currently supported by specific energy policies including a feed-in tariff for RE, energy efficiency and power conservation measures to reduce energy consumption, and a reintroduction of nuclear power to a moderate level (17–22% of generation) by 2030 [2, 3]. In addition to central government approaches to energy system design, the liberalization of the Japanese retail electricity and gas markets (2016 and 2017, respectively) has introduced energy users into the energy system design debate. Energy user's choices and behaviors will begin to directly influence the energy system. The aim of this research is to measure the potential level of this influence using both a survey and a transition theory approach, investigating user

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choice and preference impact on future energy system outcomes, and contrasting these potential outcomes with a business as usual, policy-driven energy system design approach.

19.2 Background

Following just 5 years after the Fukushima incident, the liberalization of the Japanese energy market means that the “big ten” regional retailers now face competition with smaller retailers and startups who may attract customers through pricing and energy mix-based incentives. Liberalization incorporates the retail electricity market (from April 2016), the retail gas market (April 2017), and finally the unbundling of transmission and distribution from electricity generation in 2020.

To date, energy policy has been largely guided by a top-down process, implemented by central government. This research seeks to identify the influence of energy market liberalization and changing user choices and participation preferences on a bottom-up approach to energy system design. The study uses transition theory and an assessment of specific socio-technical regimes as a lens in order to identify aspects which may help drive the transition to a low-carbon future in Japan.

Previously, Japan’s transition progress has been comparatively assessed with other large-scale deploying nations of renewable energy. The Japanese transition was found to have a strong, effective feed-in tariff in place but is lagging in terms of current progress and policy ambition for the future [4]. To meet the deep GHG cuts required by 2050, the Japanese energy system must materially change to introduce more renewable and low-carbon technologies in order to avoid reliance on less palatable options such as nuclear power.

This research recognizes that Japan’s transition is likely following a transformation or reconfiguration pathway [5], and as such, maturing RE technologies (predominantly wind and solar) are gradually being incorporated into the grid, replacing fossil fuel generators. It is intended that this gradual incorporation of RE sources will meet energy policy goals and address climate change issues.

When the Japanese energy transition was placed under further scrutiny through a “multilevel perspective analysis,” investigating the exogenous, niche technology, and socio-technical regime aspects, it was found that even extreme exogenous impacts such as the Fukushima incident do not engender rapid transition as might be expected [4, 6]. In the case of Fukushima, the anticipated rapid shift to RE was not experienced, and greater reliance on fossil fuels and energy efficiency was the actual outcome. In addition, a follow-up survey demonstrated a lack of appetite for change in the affected populace, with most people reporting that they were not likely to change electricity companies or withdraw their support from existing policy implementers (local, state, and national; [7]). Considering these findings, and the insufficient policy goal ambition to engender a successful transition in Japan, a survey was undertaken to (1) re-evaluate the appetite toward change of energy provider, (2) identify market participation preferences, and (3) clarify preference toward technologies deployed in the market to address climate change. Further, the survey identifies the reasoning and factors behind these choices with the aim of developing robust, alternative future transition scenarios.

19.3 Methodology

The methodology employed in this study is in three parts:

1. Japanese energy use, choice, knowledge, and participation survey (analysis of energy choice and participation aspects—defined in Sect. 19.3.1).
2. Scenario building (relying on current Japanese energy policy documents and goals to 2050 for the "probable" scenario and on survey findings for the "desirable" scenario—defined in Sect. 19.3.2).
3. Scenario evaluation (A holistic, comparative sustainability evaluation of scenario outcomes—defined in Sect. 19.3.3).

19.3.1 Householder Survey

One year after the liberalization of the retail electricity market, and coinciding with the liberalization of the retail gas market, a survey was undertaken to measure householder's energy use, choice, knowledge, and participation in the future energy system. Stratified sampling was used to achieve a representative sample of the population, and 4148 responses were received from across all 47 prefectures of Japan. The survey is divided into five sections: (1) social and environmental issues, investigating global- and national-scale issues and environmental awareness; (2) energy knowledge, investigating technology, policy, and energy market awareness; (3) energy use, investigating types and purpose of energy use in the home and for transport as well as opinions about energy cost; (4) energy choice, investigating the choice of energy supplier, deployment of household renewables, and reasoning for choices; and (5) the future energy system, investigating participation in energy system reform activities, preferences about the future energy mix, the future of liberalization, and policies and technologies to address climate change. Only Sects 19.4 and 19.5 of the survey are analyzed to build the scenarios for use in this study.

19.3.2 Scenario Building

All scenarios are described from the base year 1990 to the target year of 2050, in 5-year increments, and are expressed in terms of the power source mix for final energy demand in Japan.

19.3.2.1 Probable Future Scenario

This scenario is built upon the Long-term Energy Supply and Demand Outlook, which provides an electric power demand, power source mix, and commensurate GHG reduction estimates out to the year 2030 [3]. These trends are modeled and extended out to 2050 using Markal-Times Japan to derive a cost-optimized system in 5-year increments which does not include the construction of any new nuclear facilities [8].

19.3.2.2 Desirable Future Scenarios

This scenario is similar to the planned Japanese transition as described in the probable scenario; however from 2020 the power source mix is varied to mitigate climate change impacts based on end-user preferences. The quanta of these changes out to 2050 are based on the incorporation of a range of participation preferences in three specific energy system activities (demand response, household battery operation, and energy self-sufficiency). Additional potential for RE deployment, reduced consumption, and subsequent CO_2 reductions within the household sector is then determined, allowing for comparison between the desirable and probable scenarios.

19.3.3 Scenario Sustainability Evaluation

Finally, the two scenarios are subject to a comparative sustainability analysis, using the Energy Policy Sustainability Evaluation Framework [9]. This framework considers the economic, environmental, and social aspects of each energy system scenario, providing a sustainability and policy burden assessment in addition to the economic and environmental outcomes for each 5-year increment in each scenario. The framework evaluates the sustainability impacts of employment, environmental improvement, health, subsidy allocation, energy prices, and participation (impacts are derived from [9] and confirmed through a survey of energy experts in Japan; participation outcomes are expressed through scenario energy mixes, and subsidy allocation is not specifically investigated as the feed-in tariff (FiT) and other subsidization policies are not certain out to 2050).

The sustainability impacts are evaluated in a quantitative manner, expressing outcomes in terms of the change in overall sustainability and allocation of policy costs per income quintile in Japan. In this way, each scenario can be objectively assessed, and trade-offs between environmental, economic, and social aspects can be identified, allowing for proactive policy and system design to be undertaken, cognizant of policy goals and end-user preferences. The sustainability factors, their distribution, and weighting values are shown in Table 19.1.

Table 19.1 Sustainability factors, distribution, and weighting

Sustainability factor	Distribution value	Comparative weighting value
1. Employment	Job allocation and salaries	RE jobs gained—fossil jobs lost
2. Environmental improvement	Assumed to be equal	% CO_2 reduction since 1990
3. Health	Assumed to be equal	% PM_{10} reduction since 1990
4. Subsidy allocation	Not specifically investigated due to future policy uncertainty	
5. Energy price increase	% income spent on electricity	Change in energy price (LCOE)
6. Participation	Reflected in the scenario energy mix	

Sustainability factor values are determined for each income quintile in Japan using the following formulae:

$$\mathrm{SV}_{(i,j)} = \mathrm{DV}_{(i,j)} \times \frac{\mathrm{WV}_{(i,j)}}{\mathrm{MaxWV}_{(j)}} \tag{19.1}$$

where SV is the sustainability value; DV and WV are the distribution and weighting values, respectively; i is the income quintile from 1 to 5; and j (1 to 6) are the sustainability factors, as described in Table 19.1. Using the derived sustainability values for each income level, relative sustainability for each scenario can be established; thus:

$$\text{Relative sustainability}_{(i)} = \frac{\mathrm{SV}_{(i,j)}}{n_{(j,w)}} \tag{19.2}$$

where n_j is the number of sustainability factors and w is the weighting assigned to each factor according to social preference (assumed to be equal in this research, based on energy policy expert stakeholder feedback).

Relative sustainability values can then be plotted for each income quintile, and a centroid of the plotted polygon can be derived using geometric decomposition. This is achieved by using the x and y coordinates of income and relative sustainability values in an area-weighted approach. The final centroid is expressed as an x- and y-value and determined; thus:

$$x = \frac{\sum C_{k_x} A_k}{\sum A_k},\ y = \frac{\sum C_{k_y} A_k}{\sum A_k} \tag{19.3}$$

where C is the centroid and A is the area of individual geometrically decomposed rectangles k, within the polygon.

Finally, to express the resultant sustainability outcomes in an easy to compare manner on a scatter plot, the x-value (scenario policy burden) is subtracted from the ideal value of 100 to determine whether the burden imparted by sustainability level change is borne by higher (a scenario policy burden score > 50)- or lower (a policy burden score < 50)-income quintile households. The y-value is normalized to give a maximum value of 100 for relative sustainability.

The plotting of centroids illustrates the relative sustainability level for each energy system scenario, as well as the distribution of energy policy burden across income quintiles, allowing for easy comparison for each 5-year interval, and as a vector over time as described in detail in the results section.

19.4 Results

The results section is presented in three parts, firstly addressing the key survey findings for energy choice and the future energy system followed by scenario building based on current Japanese energy policy and survey outcomes. Finally, a sustainability evaluation is undertaken for both the probable and desirable energy scenarios.

19.4.1 Key Survey Findings

19.4.1.1 Energy Choice

This section of the survey predominantly assessed respondent's choices with regard to changing electricity provider after liberalization, deploying household solar and the reasoning behind their choices. In both cases, those who had actively changed their provider or installed PV, the strongest reason was cheaper electricity, economic benefits, or a desire to install (in the case of PV). For those who did not change provider or install PV, similarly, a lack of significant merit and insufficient or difficult to understand information regarding these choices were cited as the main reasons. The percentage of respondents who had changed providers (11.3%) and who had installed PV or were going to install in the near future (12.2 and 3.1%, respectively) suggest that there is a small "active" group of energy market participants who are interested in the liberalizing of the market and the deployment of new technologies, while the majority of consumers have a much more passive stance.

19.4.1.2 The Future Energy System

In the final section of the survey, respondents were asked to identify their preference for the future energy mix in terms of the technologies that they would like to see increase or decrease within the grid (Fig. 19.1).

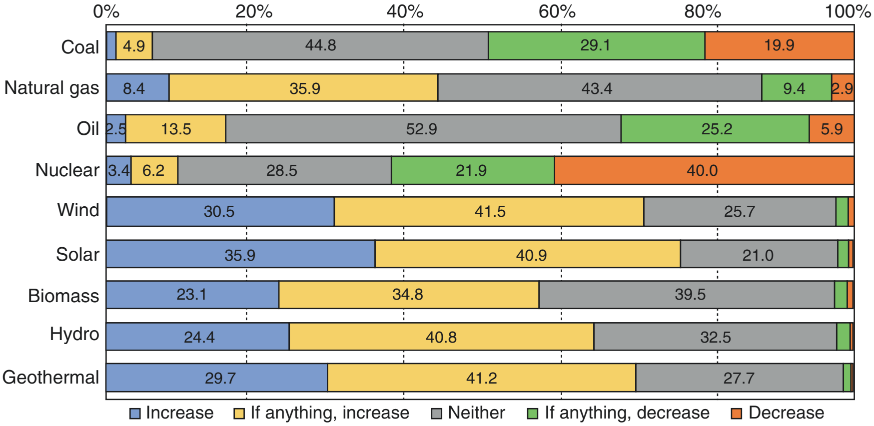

Fig. 19.1 Future energy mix preferences ($n = 4148$)

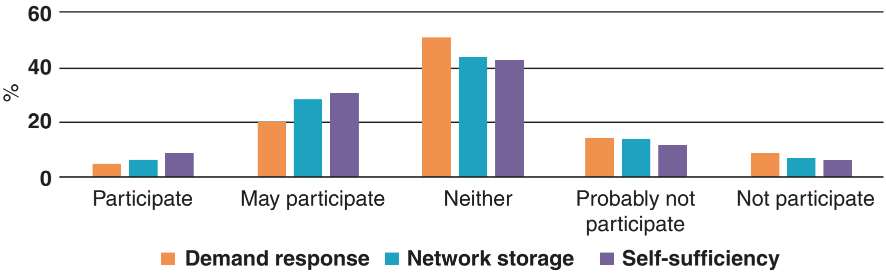

Fig. 19.2 Future energy system participation rate ($n = 4148$)

An increase in all RE sources was heavily supported for reasons of safety, natural energy use, and environmental improvement. Coal and oil were opposed due to high GHG emissions, and nuclear was heavily opposed due to the perceived danger. Natural gas was considered necessary to stabilize the power supply. From these findings, the desirable future scenario will increase energy supplied from RE in the order solar → wind → geothermal → hydro → biomass and decrease generation from undesirable sources in the order nuclear → coal → oil. LNG generation will be the same as for the probable scenario to 2050.

In addition to an energy mix preference, three post-liberalization scenarios were also tested with respondents as shown at Fig. 19.2.

Self-sufficiency was the most popular activity, followed by network storage and finally participation in a demand response initiative. Energy mix and participation preferences are applied to the desirable future scenario.

19.4.2 Future Energy Scenarios

19.4.2.1 Probable Future Scenario

Taking the Long-term Energy Supply and Demand Outlook generation mix to 2030, and then optimizing for cost to 2050 including the use of nuclear facilities to end of lifetime, gives an example of a probable future energy mix as shown in Fig. 19.3.

Following the Fukushima incident, the use of nuclear energy is restored, gradually reducing as assets reach their expected lifetime. PV and wind increase over time, while no new construction of hydropower is expected. According to the most cost-effective CO_2-reducing energy sources, LNG increases, from 2030 IGCC with CCS begins to replace coal, and hydrogen is also generated from best-cost sources for use in the stationary energy and transport sectors [8]. As a result, CO_2 emissions from power generation are reduced by approximately 4.9% compared to 1990 levels.

19.4.2.2 Desirable Future Scenario

The first step in determining the desirable future scenario is to determine the additional quanta of RE which could reasonably be deployed due to household's participation in the two future energy system activities of system-operated battery deployment (battery) and self-sufficiency (SS). A reduction in energy consumption is also calculated for demand response (DR) participation levels. Based on the key survey findings, particularly the participation preference indicated at a "participate" and "may participate" level, the quanta of additional RE are to be introduced into the grid, and consumption decreases can be established, as summarized in Table 19.2. Demand response assumes a 4% reduction in household energy consumption based on conservative use of precedents in [10]. Battery deployment assumes a 5kWh

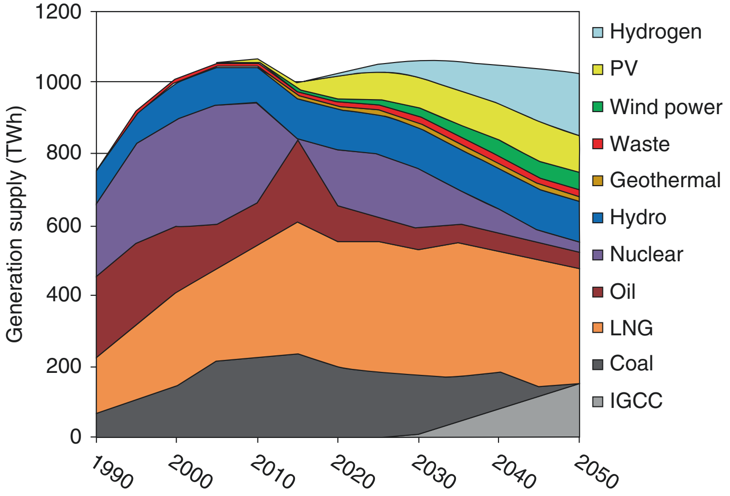

Fig. 19.3 Probable future scenario energy mix 1990–2050

Table 19.2 Activity participation and system outcomes

Factor/activity	DR	Battery	SS
Participation range (% of households)	5.2–25.6	6.3–34.6	8.5–39.1
Additional RE/reduced consumption (TWh)	0.6–2.92	6–32.7	24.3–111.6

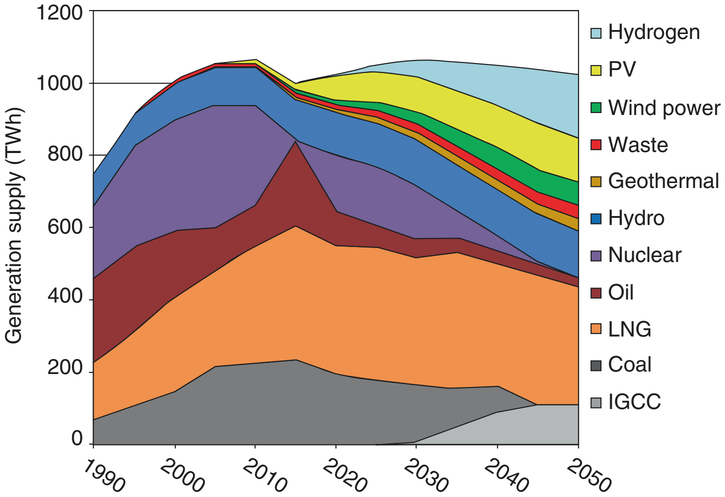

Fig. 19.4 Desirable future scenario energy mix 1990–2050

battery deployed in each participating household, cycled once (empty → full → empty) every 24 h. Self-sufficiency assumes that a solar PV array of 5 kW and battery bank of approximately 20 kW h are deployed in each participating household (sufficient to meet and provide some backup for the average daily consumption of Japanese households, 15.1 kWh [11]). Households may participate in multiple activities. Household numbers are drawn from [11].

The quanta of additional RE and reduced consumption are then distributed linearly over time to the target year of 2050 using the preferred energy sources shown at Fig. 19.1, offsetting undesirable energy sources on a 1-for-1 (TWh) basis. These quanta of additional RE or reduced consumption are expressed in a range in Table 19.2; however the energy mix scenario, shown at Fig. 19.4, uses the mean of this range as the 2050 achievement (DR, 1.76; battery, 19.35; and SS, 67.95 TWh, respectively) to illustrate a preference- and participation-based energy system outcome. The desirable future scenario reduces overall energy consumption by 2050, and the reduction of undesirable generation options leads to an earlier phaseout of nuclear power and non-IGCC generation options, while reliance on oil generation is reduced by 41.3% in 2050. All RE generation options are increased to make up for the loss in non-fossil-based generation. PV and wind increase their overall share, geothermal-based generation is approximately doubled, and the biomass contribution is increased by 70% (both of comparatively small initial contributions), as shown in Fig. 19.4.

Due to the changes engendered by household energy mix preferences and energy market participation, CO_2 emissions due to power generation are reduced by 8.9% compared to 1990 levels, almost double that of the probable future scenario.

19.4.3 Sustainability Evaluation

The two scenarios investigated in this study each engender a different energy system, derived from available energy generation sources. Each scenario can now be evaluated in terms of sustainability through a combined, comparative analysis of the economic, environmental, and social outcomes. As both scenarios' energy system is identical up to 2015, comparative sustainability and energy policy burden vectors are calculated from this point forward (with the first comparative sustainability centroids derived for 2020—higher scores are better in both cases). Health and environmental impact figures are calculated using specific technology carbon intensities [12] and PM_{10} emissions [13, 14] for each generation technology and are assumed to impact all members of society equally due to dispersion. Employment impacts are calculated by subtracting lost jobs in the fossil fuel industry from those gained in the RE industry, allocated according to RE and fossil fuel industry average salaries, adapted from [9]. Energy price increases are estimated using the levelized cost of electricity (LCOE) projected changes over time based on [15, 16], allocated according to the average energy charges per income quintile household reported in [11]. Figure 19.5 describes the impact allocations per income quintile according to the above and the assumptions described in Table 19.1. Figure 19.6 shows the comparative sustainability and policy burden for each scenario from 2020 to 2050.

As shown in Fig. 19.6, both scenarios improve overall sustainability and policy burden outcomes when compared to 2015 levels, due to the introduction of significant

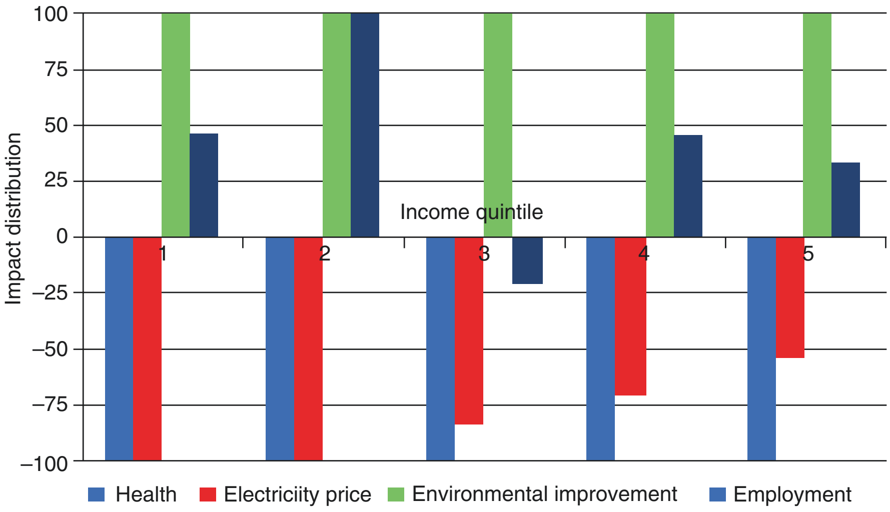

Fig. 19.5 Sustainability factor impact distribution

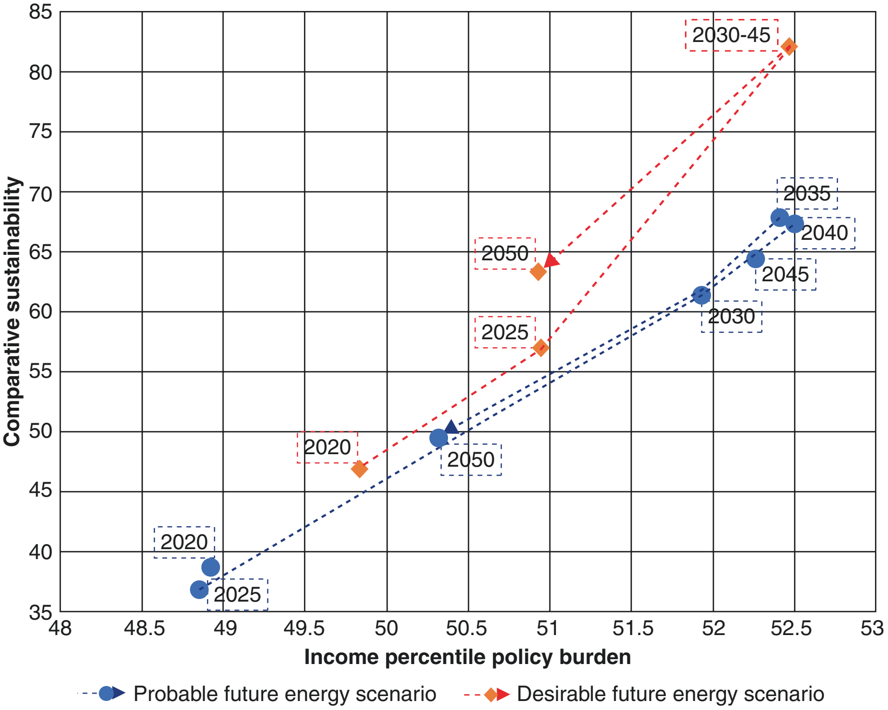

Fig. 19.6 Comparative sustainability and policy burden

RE, leading to commensurate positive health, employment, and environmental outcomes while reducing energy prices over time. Both future energy scenarios lead to an improved sustainability rating and allocation of policy burdens. An income percentile policy burden rating higher than 50 implies that higher than average-income households shoulder the majority of policy implementation costs, which has positive ramifications for social equity, shrinking the gap between rich and poor. The desirable future energy scenario is superior to the probable scenario in terms of sustainability at all stages of the timeline due to an increased overall deployment of RE, resultant from a significant increase in energy market participation by individual household. The difference in rating between the two scenarios is not constant and changes due to the fluctuation in achievement levels for each of the sustainability factors as shown in Fig. 19.7.

Both scenarios generally improve sustainability and policy burden ratings over time; however due to a reduction of overall energy industry employment numbers, a negative correction occurs from 2045 as shown in Fig. 19.5 for the desirable scenario. This negative correction is experienced from 2040 for the probable scenario due to the higher ratio of fossil fuel-based generation leading to comparatively inferior outcomes across the evaluated sustainability factors.

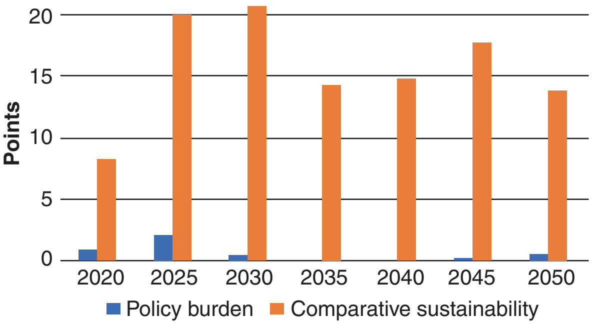

Fig. 19.7 Desirable scenario sustainability and policy burden superiority 2020–2050

19.5 Discussion

The energy mix preference shown in the desirable energy system scenario, the commensurate greenhouse gas emissions reduction, and the enhanced sustainability outcomes all demonstrate the positive impact of end-user participation in the electricity market. Participation in this research was expressed through the choice of energy generation source and level of participation in economically attractive energy initiatives which strengthen the electricity network including demand response, storage, and local generation and consumption. Assuming that end-user preferences and participation could directly influence the liberalized energy market, an additional 4% CO_2 emission reduction was realized compared to the probable future energy scenario. This additional reduction in CO_2 is significant, bearing in mind that the household sector in Japan accounts for only 15% of final energy demand [17].

With regard to sustainability outcomes, both scenarios have positive societal ramifications; for the probable future scenario through the pragmatic use of existing fossil fuel and nuclear assets, a low-cost energy system with moderate RE deployment is realized over time. For the desirable future scenario, end-user preference saw a reduction in the use of fossil fuels through a larger deployment of RE, particularly post 2030 when compared to the energy outlook envisaged in Japan. In addition, the early retirement of nuclear assets meant additional RE was deployed to meet this generation shortfall. The most influential sustainability impact factors in terms of improving sustainability outcomes between income quintiles were electricity price impacts and employment. As shown in Fig. 19.5, these two factors improve outcomes for lower-income quintiles as the energy system incorporates more RE, positively influencing employment distribution, and as electricity prices get cheaper over time, reducing financial burden. The reduction of financial burden is felt more keenly in lower-income quintiles who have a larger proportional income spend on their energy needs.

From a system design perspective, some energy policy suggestions can be drawn from the results. Firstly, participation in the energy system has significant, measurable results from an energy security, economic, environmental, and sustainability point of view. Energy policies which encourage participation through economic and other incentives which align with end-user preferences are likely to be successful in increasing RE deployment, with complementary sustainability outcomes. Care must be taken though, to ensure that barriers to participation in incentivized programs are not so high as to preclude lower-income households. The three participation programs suggested by this research have differing barriers to participation; demand response is available to all households at no cost; battery storage has an initial outlay but does not require a specific residential status, while the self-sufficiency program requires home ownership and the largest financial outlay in order to participate, potentially precluding a large portion of households. Secondly, energy policy-guided system design should incorporate a consideration of the type of RE, potential for deployment and any barriers, and employment outcomes, both in terms of direct and indirect employment. Although this research suggests significant increases in geothermal and hydropower, these may not be feasible in the timeline proposed due to construction timeframes and resource availability and accessibility (due to competing policy priorities or geographic limitations). For these reasons, future deployment of RE may need to begin with “low-hanging fruit” such as residential and mega-scale PV, biomass, and onshore wind. Deployment timelines may need to be adapted to ensure that technologies which are more difficult to deploy (offshore wind, geothermal, additional hydropower, etc.) are incorporated at feasible intervals.

19.6 Conclusion

End-user choices for their energy purchases and participation in the liberalized energy market can influence the energy system in a measurable way. This influence can be measured in terms of the energy mix and the resultant economic and environmental outcomes. Also, by looking at sustainability in a holistic manner, incorporating the distribution of impacts across income quintiles, we can start to assess whether participation and choice-driven behaviors have a positive or negative influence on energy system outcomes in terms of society and sustainability.

In this research, end-user participation and expression of purchasing choices based on economic, environmental, and other preferences were shown to have a positive impact on future energy system outcomes.

As RE costs continue to reduce in line with expanding deployment, a future energy system which incorporates large amounts of RE-based generation will also reduce energy costs for the end user, engendering a win-win outcome.

There are some limitations to this research, notably the potentially high cost of additional energy storage that would be required to enable the introduction of significant levels of intermittent RE generation and the issue of stranded assets. This research partially addresses the storage issue through the introduction of household level storage (the battery and self-sufficiency initiatives); however it is likely that these initiatives alone will be insufficient to stabilize the network, suggesting additional costs for the desirable future energy scenario when compared to the probable scenario.

A future goal of this research is the specific investigation of policy-based incentives including FiT settings and economic incentives tied to participation initiatives, further strengthening the sustainability and policy burden analysis to better inform energy system design.

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Chapter 20
The Proposal of Environmental Evaluation of Household Fuel Cell Considering Life-Cycle Analysis and Process Designing

Kiyofumi Sato, Yuna Seo, and Kiyoshi Dowaki

20.1 Introduction

In recent years, global warming has become a serious problem. Under the Paris Agreement, adopted on December 12, 2015, and constructed on November 4, 2016, Japan set the goal of reducing greenhouse gas emissions by 26% [1]. GHG emissions in the household sector have been increasing. CO_2 emissions in the Japanese household sector accounted for approximately 15% of the total emissions in 2015 [2]. From 2012 to 2014, the GHG emissions decreased slightly, but overall it is on an upward trend [3]; it is necessary to take measures to reduce GHG emissions in the household sector.

As a countermeasure for GHG mitigation, fuel cell power system (FCs) is one candidate. For instance, a polymer electrolyte fuel cell cogeneration system (PEFC-CGS) and/or a solid oxide fuel cell system (SOFC-CGS) begin to be sold in the domestic market. These systems are known by "Ene-Farm" and "Ene-Farm type S."

This device can generate power through chemical reaction of hydrogen and oxygen, and simultaneously thermal energy can be produced. This thermal energy is converted to hot water and supplied to the house.

Also, their system has a good potential to promote in not only the domestic market but also EU countries. According to the report of Fuji Keizai Co., Ltd., the market of FCs for residential application was 41.9 billion yen in 2014, and it is expected that the market will expand to about 79 times in comparison to that as of 2014 as much as 251 billion yen in 2030 [4].

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However, every type of FC might not achieve GHG emission abatement, because the device varies in specification according to manufacturers, including the performance, the durability, etc. Thus, in this study, the specification which is influenced to the performance attributed to the effect of GHG emission abatement was discussed. Note that the environmental performance would be affected by the constituent materials associated with the specification and/or operation though the cost would be an important factor.

Based on these backgrounds, the International Electrical Committee/Technical Committee (IEC/TC) has tried to establish LCA index to improve the quality. That is, the visualization of eco-burden index of FC-CGS which would be based on product category rule has developed. In the previous studies, it is known that the indirect CO_2 emissions are negligible in comparison to the direct ones [5]. On the other hand, in our proposed index, it is necessary to reflect the factors on constituent materials in the index besides CO_2 emission. To identify the best system which has more eco-benefits among the same devices, it is necessary to consider the relationship between operational performance and environmental impact. We chose abiotic depletion potential (ADP) to express those, which is well represent the influence of the use of rare metals.

In PEFC-CGS, the index of ADP in an impact category would be affected due to the consumption of Pt (platinum) used in the cell surface as a catalyst. Also, in the case of SOFC-CGS, the metals of Cr (chromium), Ni (nickel), etc. would be high impacted to ADP. Note that the value of ADP is calculated by multiplying the consumption weight with the intensity of impact. Thus, considering the combination of the different factors, data envelopment analysis (DEA) was used. DEA compares service units considering all resources and services provided and identifies the most efficient units or best practice units and the inefficient units in which real efficiency improvements are possible. This is achieved by comparing the mix and volume of services provided and the resources used by each unit compared with those of all the other units. Here, the input resources are the indirect CO_2 emission and ADP in the manufacturing stage. The service provided is the CO_2 emission mitigation [6]. Using DEA, which is defined as FC-DEA, our scenarios on FC-CGS promotion were analyzed.

Finally, the consumers who will purchase FC-CGS can select the best device on the basis of the environment and operating performance factors. On the other hand, the manufacturers can understand the points which have to be improved so that their systems will be chosen by the customers.

20.2 Analytical Conditions

20.2.1 Specification of FC-CGS

In this study, PEFC-CGS (Ene-Farm) and SOFC-CGS (Ene-Farm type S) of the rated output of 0.7 kW with their performance guarantee of 10 years (90,000 h) were estimated as shown in Table 20.1. On the specification of each FC-CGS, the product specification of PEFC-CGS by Tokyo Gas Co. Ltd. or specification of SOFC-CGS by Osaka Gas Co. Ltd. was used as a reference data [7, 8]. Also, on the material data of PEFC-CGS, the report by Mizuho Information & Research Institute was referred [9] and that of SOFC-CGS was based on the studies of Young et al. [10], Karakoussis et al. [11], and the hearing data by the manufacturer.

On the operation performance, the power and heat recovery efficiencies in case of PEFC-CGS are assumed to be 39% and 56% LHV. Those in SOFC-CGS are 52% and 35% LHV. In addition, PEFC-CGS can pursue the electricity demand change to some extent. The operation range is between 100% and 30% for the rated output of 0.7 kW. That is, this means that the device is suspended if the electricity demand is 0.21 kW below. This behavior can be expressed due to the process design profile due to the IV characteristic on PEM cell based on the experiment. Accordingly, the optimal operation of PEFC-CGS was considered in this paper [6]. Inversely, SOFC-CGS is constantly operated due to the specification limitation. Note that the excess energy supply was negligible in both cases (Table 20.1).

20.2.2 Energy Demand

Regarding the energy demands on electricity and hot water supply in a household (single family), the standard load patterns of electricity and hot water supply were based on the data defined due to the energy efficiency measurement method (Japan Industrial Standard: JIS C 8851) for FC-CGS. In these load patterns, the following three seasonal data were considered: summer of 92 days (July, August, and September), winter of 121 days (December to March), and other seasons of 152 days (April to June, October, and November), respectively [12].

Table 20.2 shows the definitions in a targeted household, and Figs. 20.1 and 20.2 show the demand patterns of electricity and hot water supply. Note that each load pattern is an hour basis data in each season.

In electricity demand, the power of air conditioner and other electrical applications is considered. In hot water, the thermal energy is due to a shower, a kitchen, a washbasin, and a bath. Here, the annual electricity demand is 6533 kWh/year. (23,527 MJ/year) and that of hot water supply is 4649 kWh/year. (16,735 MJ/year), respectively [12].

Table 20.1 Product specifications of PEFC-CGS and SOFC-CGS sold in Japan [7, 8]

	PEFC-CGS	SOFC-CGS
Type	PEFC	SOFC
Usage form	Home use	Home use
Years	10 years	10 years
Fuel type	City gas 13A	City gas 13A
Rated output	700 W	700 W
Hot water storage tank capacity	140 L	28 L

Table 20.2 Conditions of target home [12]

Area	Kanto
Construction method	Detached house
Household size	Husband (worker)
	Wife (housewife)
	Eldest daughter (high school student)
	First son (junior high school student)
Schedules	Weekday NHK citizen lifetime survey, etc.
Seasons	Summer 92 days (July, August, and September), 152 days (April to June, October, and November) in the intermediate period, and 121 days (December to March) in the winter

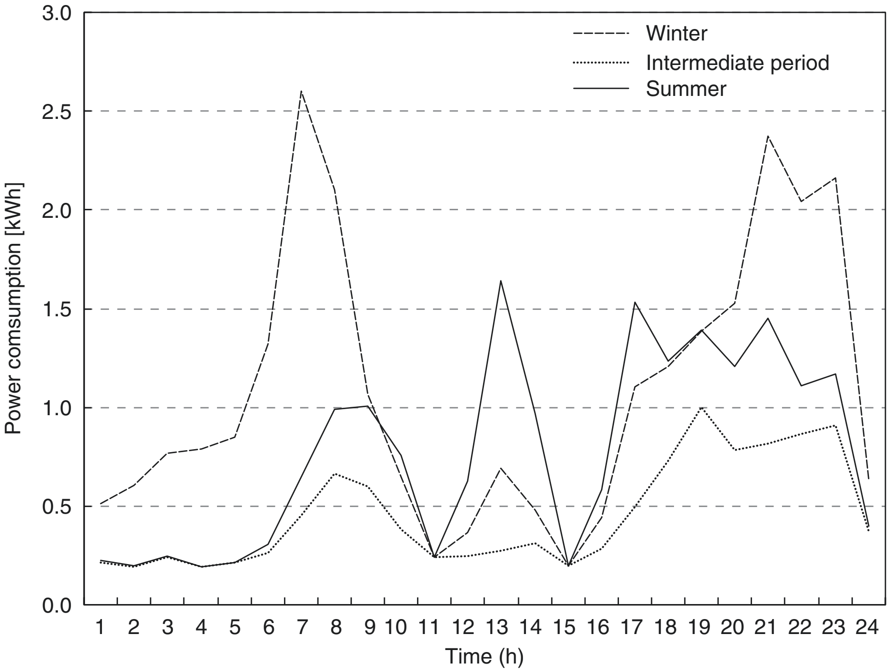

Fig. 20.1 Electricity demand (single-family home) [12]

Using these patterns, the energy supply is assumed in this study. Note that the excess energy supply is assumed to be wasted and that the lack of energy is compensated by the conventional energy system (e.g., the conventional grid or the gas boiler). This is due to the current regulation.

20.3 Analytical Method

A basic concept in this paper is to compare FC-CGSs which were manufactured by several makers from the viewpoint of eco-burden and its operating performance.

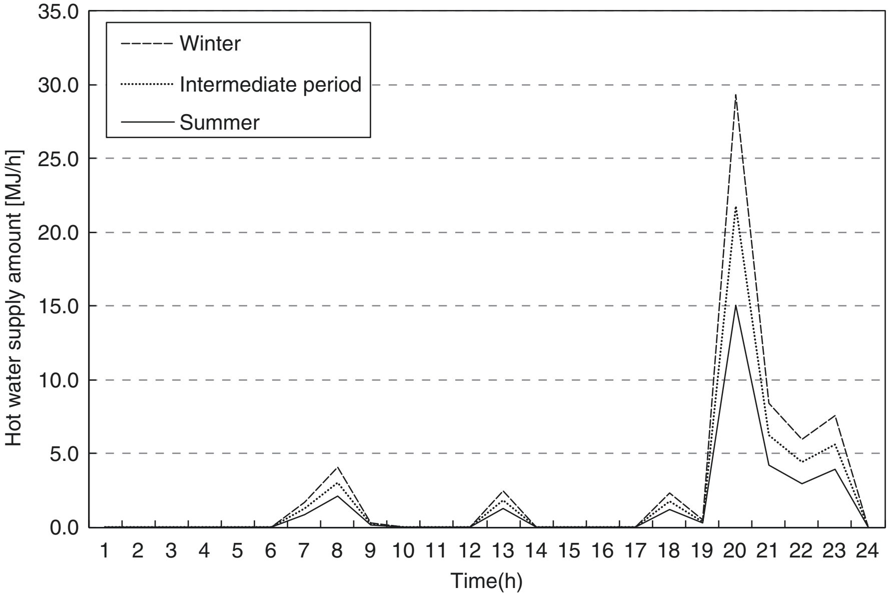

Fig. 20.2 Hot water supply (single-family home) [12]

That is, the consumer would be able to choose the better product in use of our proposed index of FC-DEA.

Here, the analytic procedures were carried out based on the following three steps: First, the four scenarios on PEFC-CGS and SOFC-CGS were set according to the different structures of cell stacks. Second, the LCIA (life-cycle impact analysis) on the manufacturing stage in each scenario was executed. Note that the adopted impact categories were based on the five influence ones defined in FC-Guide [13]. Third, the direct CO_2 emission reduction in comparison to the conventional energy supply system was simulated so as to meet the energy demands. Note that the operating performance in each FC-CGS is associated with the direct emission reduction. Finally, FC-DEA by which the efficiency can be expressed was estimated.

20.3.1 Setup Scenarios

In this paper, on the FC-CGS which has high potential, the following four scenarios were set up in consideration of the current R&D situation. Also, the standard rated output is assumed to be 0.7 kW considering the promotion status in the recent years.

20.3.1.1 Scenario 1 (Reference)

This scenario is a reference case. That is the PEFC-CGS of 1 kW of which LCA was executed on basis of the previous data [9]. Note that the inventory data was adjusted so as to meet the standard output. That is, the weight consumption of material was converted to the value in accordance with the 0.6 power rule.

20.3.1.2 Scenario 2

In this case, it is assumed that the Pt weight of reference case was reduced to 1/10 [6]. The weight of constituent materials besides Pt is the same value as the reference case.

20.3.1.3 Scenario 3

Scenarios 3 and 4 are for SOFC-CGS cases. The difference of these cases is the specification of cell stack. In this case, the type of cell stack is the planar. Based on the previous studies, the material data and/or the specification were determined [10, 11]. Also, as with the case of PEFC-CGS, these parameters were adjusted to meet the rated output of 0.7 kW. In general, in the SOFC operation, the device cannot pursue to the load change. The lifetime was assumed to be 8 years due to the hearing data from manufacturer.

20.3.1.4 Scenario 4

In Scenario 4, the type of cell stack is the anode-supported one. Likewise, the data for inventory analysis was based on the previous studies [10, 11]. From the operating performance, the SOFC-CGS with the cell stacks of this type seems to be preferred in the current promotion status in Japan.

20.3.2 Life-Cycle Assessment (LCA)

20.3.2.1 Summary

In this paper, the system boundary is limited, since the purpose is to identify the FC-CGS for household from the operating condition and environmental aspects (see Fig. 20.3). This means that the identification becomes clearer, if the related stages are chosen appropriately. That is, in this study, the elements of system boundary are only the stages of manufacturing and using. In the manufacturing stage, the data on constituent materials was estimated based on relevant literatures, because almost data was confidential.

Also, the functional unit is the energy supply for 10 years through a FC-CGS unit whose rated output and lifetime are 0.7 kW and 10 years. However, the adjustment

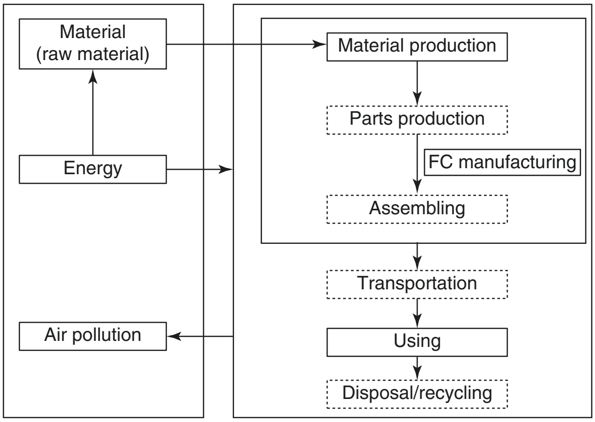

Fig. 20.3 System boundary

of results should be necessary to integrate the lifetime of PEFC-CGS, since the lifetime of SOFC-CGS is assumed to be 8 years. That is, in the case of SOFC-CGS, the inventory values were estimated by multiplying the year basis values with 10/8. The procedures of this LCA were referred to ILDC Handbook and/or FC-Guide [13, 14]. Note that the commonly used software of SimaPro ver. 8.3.0.0 with the database of Ecoinvent 3.3 was used [15, 16]. Here, the weight consumption data list used in the inventory analysis is shown in Table 20.3. The impact assessment was adopted by the CML methodology, and "global warming potential (GWP: 100 years)" and "abiotic depletion potential (ADP)" were estimated. The reason why these impact categories were adopted is to make the differences on the specification and performance in each scenario.

20.3.2.2 Manufacturing Stage

Next, using the weight data, the input factors of FC-DEA were estimated. That is, the indirect factors due to the difference of specification in each scenario were calculated.

In the PEFC-CGS, Pt used for catalyst is most impacted in the indirect factors. In fact, the indirect CO_2 emission of Pt is very small at the manufacturing stage; however the performance is greatly affected. Madhu et al. pointed out that the increasing of utilization rate of Pt can be achieved to reduce the weight, which is a noble metal used on the surface of fuel cell, for commercialization of PEFC-CGS [17]. Jinno et al. executed the identification of PEFC-CGS unit in the use of ADP and GWP, since Pt has the environmental impact value [6]. Therefore, in Scenarios 1 and 2, the influence of weight change of Pt was discussed. Especially, the New Energy and Industrial Technology Development Organization (NEDO) projected that the Pt can be reduced to 1/10 in comparison to the current level without the operation performance drop [18]. Here, the scenarios' setup is based on this aspect.

Table 20.3 Weight of constituent materials in each scenario [9–11]

(a) Scenarios 1 and 2 (PEFC-CGS) [kg/unit]				
Scenario			1	2
Fuel cell unit	Cell stack		16.15	16.15
		Reforming unit	13.97	13.97
	Others	Inverter	5.01	5.01
		Pump, blower	7.67	7.67
		Heat exchanger	6.46	6.46
		Exhaust heat recovery device	6.46	6.46
		Wiring cable	8.07	8.07
		Case	24.22	24.22
		Water treatment equipment	2.91	2.91
	Fuel cell unit total		90.91	90.91
Hot water storage unit	Hot water tank		112.62	112.62
	Backup burner		14.61	14.61
	Hot water storage unit total		127.24	127.24
Total			218.14	218.14
(b) Scenarios 3 and 4 (SOFC-CGS) [kg/unit]				
Scenario			3	4
Fuel cell unit	Cell stack		22.36	4.59
		Casing	8.07	NA
		Pressure vessel	NA	40.37
		Pressure vessel insulation	NA	0.40
		Air and fuel supply system	16.15	1.61
		Air plenum assemblies	NA	3.39
	Others	Stack reformer boards	NA	0.16
		Desulfurizer	0.48	0.0048
		Pre-reformer/gas burner	4.44	NA
		Heat exchangers	3.23	3.23
		Power conditioning system	0.27	0.27
		Conventional gas heating unit	40.37	NA
	Fuel cell unit total		95.37	54.03
Hot water storage unit	Hot water tank		42.88	42.88
	Backup burner		0.59	0.59
	Hot water storage unit total		43.47	43.47
Total			138.83	97.65

Next, in the SOFC-CGS, Kitahara et al. described that the conductivity change depends upon the amount of Ni used in the anode [19]. Also, the amount of Cr used for the interconnect is affected in terms of the performance [20].

As the above, it is important to discuss the rare metals used in the cell stacks of PEFC-CGS and SOFC-CGS in terms of their performances. For these aspects, the indication on basis of LCA should be necessary.

20.3.2.3 Using Stage

First, on the PEFC-CGS, based on the process simulator (Excel-VBA 2013) in consideration of the IV characteristic of PEM cell, the direct CO_2 emission reduction of PEFC-CGS (using stage) was estimated. Note that this calculation was performed by comparing to the conventional energy supply (electricity and hot water) of fossil fuel origin. On the CO_2 emission of PEFC-CGS, the optimization model in use of the software of GAMS Ver. 23.0.2 was developed, and the Eq. 20.1 was solved so that the emission reduction is at maximum.

$$\max.\left(\mathrm{Total\_Conv}_{\mathrm{CO_2}} - \mathrm{Total\_PEFC}_{\mathrm{CO_2}}\right) \tag{20.1}$$

$\mathrm{Total\_Conv}_{\mathrm{CO_2}}$: Conventional case CO_2 emissions kg CO_2 eq/year
$\mathrm{Total\_PEFC}_{\mathrm{CO_2}}$: CO_2 emissions when introducing PEFC-CGS kg CO_2 eq/year

Next, on the case of SOFC-CGS, as explained before, the constant operation was assumed, and the excess power supply was negligible. Likewise, the direct CO_2 emission reduction in this case was obtained as Eq. 20.2.

$$\max.\left(\mathrm{Total\_Conv}_{\mathrm{CO_2}} - \mathrm{Total\_SOFC}_{\mathrm{CO_2}}\right) \tag{20.2}$$

$\mathrm{Total\_Conv}_{\mathrm{CO_2}}$: CO_2 emissions when introducing SOFC-CGS kg CO_2 eq/year

The fuel of PEFC-CGS and SOFC-CGS including the backup boiler is natural gas.

20.3.2.4 Data Envelopment Analysis (DEA)

FC-DEA was based on the concept of DEA. In general, data envelopment analysis (DEA) is a linear programming-based technique for measuring the relative performance of organizational units where the presence of multiple inputs and outputs makes comparisons difficult. The usual measure of efficiency of output/input is often inadequate due to the existence of multiple inputs and outputs related to different resources, activities, and environmental factors. In this paper, the environmental impact values at the manufacturing stage were used as the input factors, and the direct CO_2 emission reduction in the using stage was adopted as the output factor. Since, due to these factors, the efficiency value cannot be calculated, FC-DEA which is defined as a relative efficiency value can be obtained by estimating each weight parameter of each factor in the use of the linear programming problem (see Eqs. 20.3–20.7). That is:

$$\max \theta = u_1 y_{1k} + u_2 y_{2k} \ldots + u_n y_{nk} \tag{20.3}$$

s.t.

$$v_1 x_{1k} + v_2 x_{2k} \ldots + v_m x_{mk} = 1 \tag{20.4}$$

$$\begin{aligned} & u_1 y_{1k} + u_2 y_{2k} \ldots + u_n y_{nk} \\ & \leq v_1 x_{1k} + v_2 x_{2k} \ldots + v_m x_{mk} \end{aligned} \tag{20.5}$$

$$v_1, v_2, \ \ldots v_m \geq 0 \tag{20.6}$$

$$u_1, u_2, \ \ldots u_s \geq 0 \tag{20.7}$$

where $x_i(i = 1,\ 2,\ \ldots m)$ and $y_j(j = 1,\ 2,\ \ldots n)$ are the factors of input and output, respectively. $v_i(i = 1,\ 2,\ \ldots m)$ and $u_j((j = 1,\ 2,\ \ldots n))$ are the weight parameters of input and output factors. The suffix k represents the number of scenarios. Assuming that the maximum value of objective function (FC-DEA) is θ^*, the scenario is determined by the most efficient model, if the result satisfies the condition of $\theta^* = 1$. The optimal solutions of $\mathbf{v}^*$ and $\mathbf{u}^*$ which are solved by Eqs. 20.3–20.7 are obtained, and FC-DEA in the target scenario is estimated [21, 22].

20.4 Results and Discussions

20.4.1 Environmental Impacts at the Manufacturing Stage

The environmental impacts at the manufacturing stage are shown in Fig. 20.4. Note that the impact categories were based on the five environmental impacts defined in FC-Guide [13].

According to these results, the environmental impacts are greatly changed in all scenarios. In this paper, the consumption of Pt or Cr in the device at the manufacturing stage was focused. That is, it implies that ADP associated with those values is a candidate of input factor in FC-DEA. Likewise, this impact is likely to be an input factor since the changes in GWP were seen.

Next, the absolute values were converted to the normalized ones to investigate the impact intensity among the target categories (*see* Fig. 20.5). The normalization methodology is considered by CML guidelines [23].

In Fig. 20.5, it was seen that ADP was high impacted among the categories. As explained, the large intensity might be due to the consumption of Pt or Cr in the FC device.

On the other hand, GWP, that is, CO_2 emission, is not a large impact. However, the emission at the manufacturing stage might have an important meaning for the improvement of the manufacturing system. The acidification which is a larger

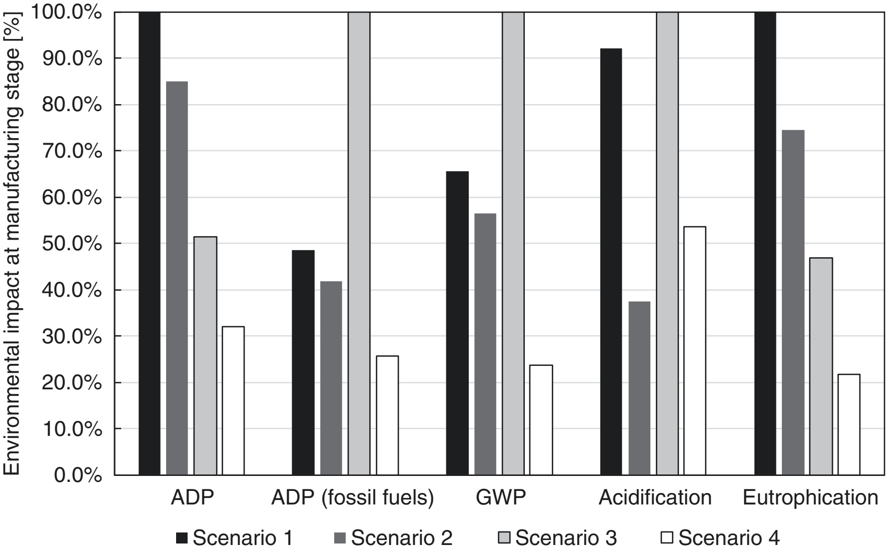

Fig. 20.4 Environmental impact at manufacturing stage

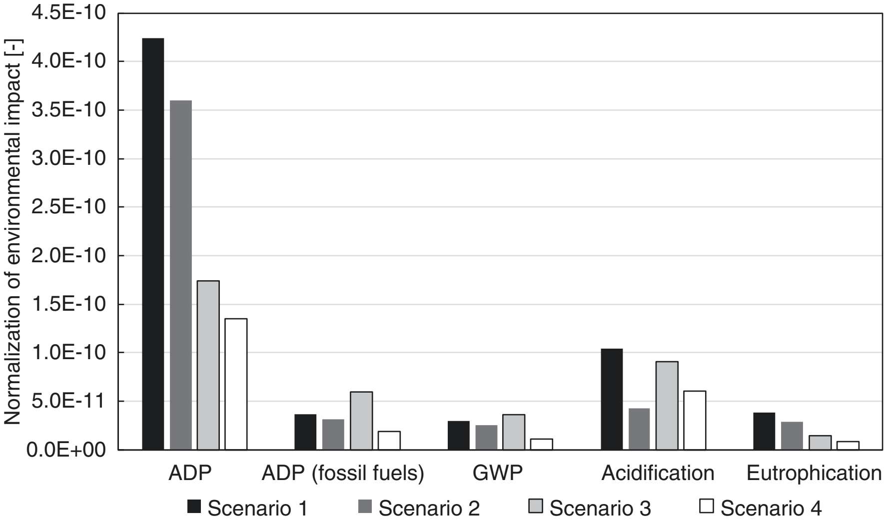

Fig. 20.5 Normalized impacts at manufacturing stage

intensity than GWP has almost the same trends as GWP. This indirect CO_2 emission would be easy to understand the eco-burden on FC-CGS to the consumers comparatively. Thus, in this paper, the impact categories of ADP and GWP were assumed to be adopted at the input factors of FC-DEA.

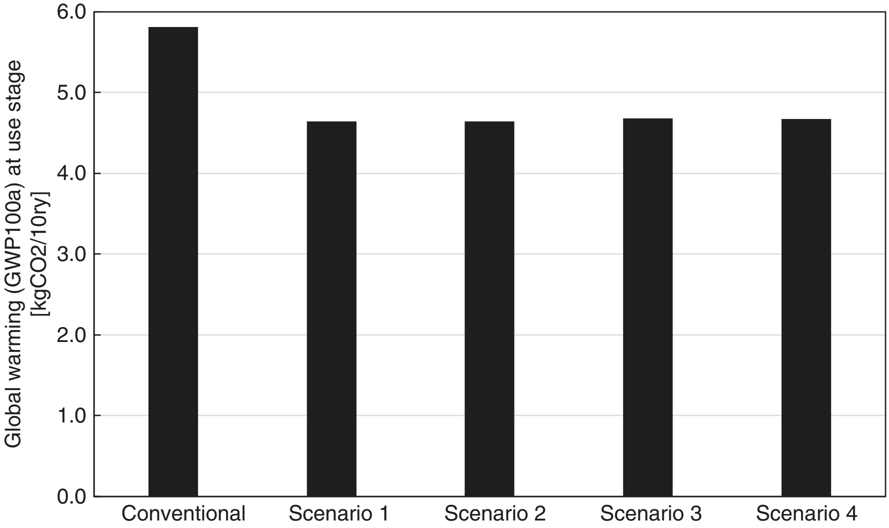

Fig. 20.6 Direct CO_2 emission at the using stage

20.4.2 Direct CO_2 Emission Reduction

On the optimal model of FC-CGS (see Eqs. 20.1 and 20.2), the direct CO_2 emission reduction was estimated in Fig. 20.6. Here, the specific CO_2 emission of conventional energy sources (grid electricity and city gas 13A) is assumed to be 500 g CO_2/kWh and 50.9 g CO_2/MJ, respectively. Note that the indirect factors at the production fuel stage were excluded on these emissions. In the promotion of FC-CGS, the benefit of CO_2 emission reduction can be obtained due to the simultaneous production of power and thermal energy (hot water). However, considering the operation range of 10 years, there was little difference in any scenarios. Consequently, these estimated results were used as output factors in FC-DEA.

20.4.3 Indicator by FC-DEA

Based on the above results, FC-DEA in each scenario was analyzed. Here, the input and output factors are shown in Table 20.4. Note that the impact factor multiplied the estimated per a unit device with 10/8 in SOFC-CGS scenario. Because the lifetime of SOFC-CGS is assumed to be 8 years, but the standard duration for this LCA is 10 years.

Finally, the results of FC-DEA were illustrated in Fig. 20.7. In our estimation, Scenario 4 was calculated as 1.0, that is, the case of SOFC-CGS using anode-supported cell stacks was the most efficient. The weight parameters in each scenario are

Table 20.4 Input and output data for DEA

DMU	Input		Output
	GWP [kg-CO_2 eq/unit]	Abiotic depletion [kg-Sb eq/unit]	CO_2 emission reduction [kg-CO_2 eq/10 years]
Scenario1	1243.16	0.089	11656.24
Scenario2	1071.35	0.075	11656.24
Scenario3	1896.54	0.046	11319.49
Scenario4	447.61	0.028	11358.57

The lifetime of unit is 10 years. In the SOFC-CGS (Scenario 3 and 4), the value is multiplied with 10/8

Table 20.5 Weight parameters in each factor

DMU	Input		Output
	v_1 ($\times 10^{-4}$)	v_2	u ($\times 10^{-5}$)
Scenario1	8.00	0.00	3.17
Scenario2	9.30	0.00	3.68
Scenario3	0.00	21.93	5.47
Scenario4	22.34	0.00	8.80

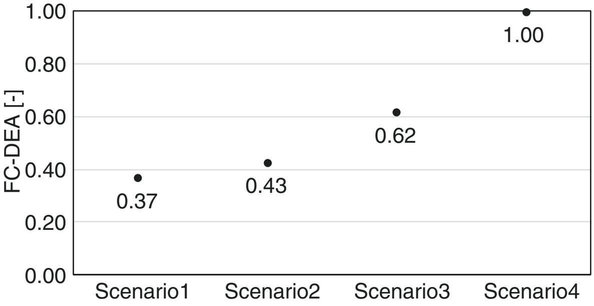

Fig. 20.7 Result of FC-DEA

shown in Table 20.5. FC-DEA in Scenarios 1, 2, and 4 is characterized by the input factor of GWP, and that in Scenario 3 is characterized by ADP. Since Scenario 4 is the most efficient, it implies that the Pt weight in Scenarios 1 and 2 should be reduced. In this estimation, the factor of ADP would not be affected by the weight of Cr. In this scenario, the countermeasure for reducing CO_2 emission at the manufacturing stage would be necessary.

20.5 Conclusion

In this paper, on the scenarios on PEFC-CGS and SOFC-CGS, the impact analysis at the manufacturing and using stages was conducted. For the performance estimation of FC-CG, the maximum CO_2 emission reduction was simulated due to the optimal energy supply model. Using these results, the multiple index for eco-burden, metal consumption, and performance was developed. This index is based on the data envelopment analysis (DEA), here, that is defined as FC-DEA.

As a result, FC-DEA in the case of anode-supported SOFC-CGS was the best efficiency value. Due to FC-DEA, the improved points would be identified. Because FC-DEA can be estimated even if the input and output factors with different functional units are selected, mutiple environmental impact categories of LCA were integrated into the single parameter for FC-DEA.

That is, this means that the best practice for consumers in consideration of the eco-burden besides CO_2 emission and/or the performance, etc. can be executed.

In our future tasks, considering the selection of more suitable factors, the identification of FC device will be done in the use of FC-DEA.

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Chapter 21
Study on a Model of Cost of Electricity for Biomass Including Learning Effect to Evaluate Feed-in-Tariff Pricing

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21.1 Introduction

21.1.1 Background

In 2012, feed-in-tariff (FIT) helped in promoting electricity generated from renewable energy sources. This system obliges electric companies to buy electricity generated from renewable sources at a fixed price for a fixed period. Biomass energy is considered a renewable resource, and the FIT mechanism that boosts it is approximately classified into three categories. One of them is "primary forest biomass," which includes construction waste. The second one is "biogas," which is generated by fermentation. The third category is "municipal solid waste" (MSW).

Although it has been 5 years since the FIT system began, FIT for biomass faces three types of problems: systematic, technological, and economic (Kajiyama, 2013) [1]. The systematic problem refers to tariffs that are classified not by capacity but by the type of fuel used. An amendment to FIT has been effective since 2017, but some biomass resources have not drastically changed their tariffs. The utility of heat, especially the cogeneration of heat and power (CHP), is not discussed or promoted. At tariff system, resource classification can occur on the technological side. Under the present tariff system, specific combustion technology will be developed, thus disturbing the development of other technologies that have potential to be more effective, but will be limited to the same level as before. The economic problem points the cost of biomass fuel is expensive. Since biomass FIT targets large plants (e.g., 5000 kW), a significant amount of biomass resources is required. Furthermore,

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fuel prices remain at a high level owing to the high demand. Thus, the scarcity of biomass remains a big concern (Ando, 2014) [2]. Yanagida et al. (2015) [3] and Mitsubishi UFJ Research and Consulting Co., Ltd. (MURC, 2016) [4] have adopted quantitative and systematic approaches to conduct research related to FIT; however, a model to calculate the tariff is still unavailable, because their reports just mention analysis for cost of electricity (COE) and do not suggest the new price system. In addition, these reports mainly investigate large-scale plants such as over 5000 kW.

Gasification process or the Organic Rankine Cycle has high conversion efficiency, and they are suitable for small-scale plant such as less than 1000 kW plants. A load map for research and development will be necessary.

21.1.2 Objective

Hence, in this study, the objectives are to clarify the process to determine the cost of COE and its components and to evaluate a reasonable tariff that targets biomass model plants with small and medium capacities. In addition, the calculation of the COE and the evaluation of a model that used a learning effect in a biomass plant are conducted for considering new tariffs or new promotion system.

21.2 Method Adopted

Current study is focused on calculations for a representative model plant, which differ from a calculation by the cost evaluation committee (hereafter, the committee) that focuses on comparing the power generation technologies. Thus, the model plant should be understood as one ideal plant that is aggregated from all domestic biomass power technologies in the country. This explains why cumulative production number of plants is just one plant. Its generating power is thought as a cumulative power generation that can be analyzed.

21.2.1 Cost of Electricity Analysis

First, the determining process for the tariff is achieved, and a mechanism to determine the COE is analyzed. Tariff is determined with COE and internal rate of return (IRR) [5]. This calculation flow excludes the business tax from the profit by selling electricity under FIT. The COE is calculated with taking into account the levelized cost of electricity (LCOE) [6]; Eq. 21.1 is

$$\mathrm{COE} = \frac{\mathrm{CAP} + \mathrm{O\&M} + \mathrm{FUEL}}{\mathrm{GEP}} \tag{21.1}$$

COE: cost of electricity (JPY/kWh)
CAP: annual capital cost (JPY/year)
O & M: operation and maintenance cost (JPY/year)
FUEL: cost of fuel (JPY/year)
GEP: generated electric power (kWh/year)

21.2.2 Overview of Our Approach for COE

Current work relies on the flow shown in Fig. 21.1, and the following describes calculation flow. The beginning in Fig. 21.1 is capacity.

21.2.2.1 Cost of Fuel

First, we follow the stream of the upper side in Fig. 21.1 to find COE. Power generation efficiency is related to capacity scale. The model plant is operated for annual hours with considering capacity factor shown as CF in Fig. 21.1, and the plant generates the gross power. CF is not found from capacity but connects it, because gross power is calculated through CF. The annual fuel consumption indicates by unit weight is found from gross power and efficiency. The fuel cost is calculated by multiplying the fuel consumption by fuel price per kilogram. The fuel price changes every year actually, but it is considered as stable price.

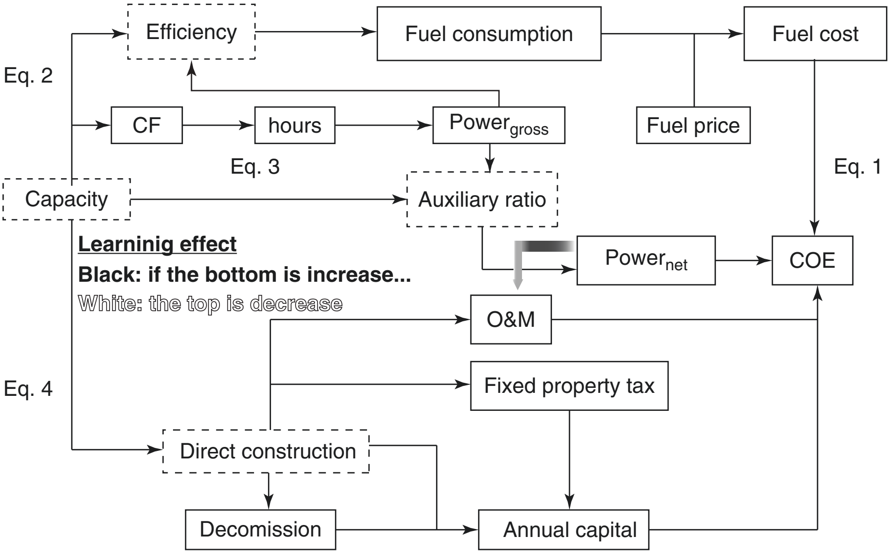


Fig. 21.1 Flow to calculate COE

21.2.2.2 Net Power Generation

Second, net power generation is calculated by following the middle stream in Fig. 21.1. The auxiliary power ratio indicates how much electricity is used in a model plant, and it relies on capacity with considering an equation as well as the efficiency. The electricity consumption in plant is calculated by capacity and auxiliary ratio. Net power is found by subtracting electricity consumption from annual gross power.

21.2.2.3 O&M, Annual Capital, and COE

Lastly, we follow the bottom stream in Fig. 21.1 to observe a flow for calculating annual capital cost and O&M cost. The construction cost, described as direct construction in Fig. 21.1, is decided by capacity scale with an equation at this work. This calculation method differs from the committee offers, because the committee uses unit construction cost per kilowatt.

The O&M indicates the summation of labor cost and maintenance cost. As described above, capacity scale decides construction cost, and required number and salary payment of operators are decided from them. Present work assumes maintenance also depends on them. Thus, O&M connects from direct construction in Fig. 21.1. In addition, the black and white allow is described from net power generation to O&M cost because of learning effect.

The fixed property tax is an annual tax for the plant and the tax rate is fixed. It depends on the direct construction cost. Construction cost is designed as an annual expense ratio, taking depreciation into account, and it takes a fixed property tax with a depreciation rate after construction. Annual capital cost is the summation of direct construction, decommission, and fixed property tax.

This allows COE to be extend from fuel cost, O&M, annual capital, and net powerto LCOE process, which described in Eq. 21.1.

21.2.3 Mathematical Formulation

Based on the work of the committee [7], the flow to calculate the COE is shown in Fig. 21.1. An explanation is provided below.

21.2.3.1 Cost of Fuel

Power generation efficiency reflects the capacity of plants, as shown in Eq. 21.2 [4]:

$$\mathrm{Eff} = 10.39\ \log_{10}\mathrm{Capacity} - 13.04 \tag{21.2}$$

Eff: power generation efficiency (%)

Capacity: plant capacity (kW)

The gross power generation is calculated by multiplying capacity by operation hours and a capacity factor. The consumption fuel weight is determined by the gross power generation, efficiency found by Eq. 21.2, and heating value that is not shown in Fig. 21.1. The cost of fuel is estimated by multiplying the fuel weight and by the fuel price.

21.2.3.2 Net Power Generation

An auxiliary power ratio is also reflected by the capacity as shown in Eq. 21.3 [4]:

$$\mathrm{AR} = 0.1649\exp\left(-5.298\times10^{-6}\times\mathrm{Capacity}\right) \tag{21.3}$$

AR: auxiliary ratio (%)

The net power generation is determined by the auxiliary ratio and gross power generation.

21.2.3.3 Annual Capital Cost

The construction cost is initial investment. When construction costs were considered, the committee made use of unit construction cost and capacity. In present work, the direct construction cost is considered instead of usual construction cost as shown in Eq. 21.4:

$$\mathrm{Const} = 23.37\times10^{8}\times\left(\frac{\mathrm{Capacity}}{5700}\right)^{0.6763} \tag{21.4}$$

Const: direct construction cost (JPY)

The direct construction cost in this point is different from OECD and others, because they calculate the initial investment before construction [8]. The decommission cost, which is the cost required for decommissioning a plant, can be calculated using the expense ratio and the construction cost. The depreciation, decommission, and fixed property tax are called the annual capital cost. In other words, the term indicates that the tax is not apparently shown, and it is included in the CAP in Eq. 21.1.

21.2.3.4 O&M Cost

In current study, labor cost is fixed for temporary use, and maintenance costs can be calculated by multiplying a rate by the construction costs.

21.2.3.5 COE

The discount rate helps in deriving the present value for each annual cost. It is determined by Yanagida (2015) as reference. It is assumed that a plant operates for 20 years because FIT guarantees the payment for the duration years that differs from lifetime regulated by law. The summation of the direct construction cost, O&M cost, and cost of fuel during this period is accounted as the cost. When the summation and generated electricity power are merged into Eq. 21.1, the COE can be calculated.

21.2.4 Cost of Electricity Analysis

21.2.4.1 Parameters

Based on the work of the committee, the COE estimation uses a plant capacity of 5000 kW. Thus, the method of calculation lacks versatility because its efficiency, auxiliary ratio, and construction cost are all designed for 5000 kW capacity plants. Then, present work estimates the COE for other capacities with Eqs. 21.2–21.4 based on MURC (2016). It should be noted that the estimation of a 5700 kW capacity plant is used as a standard to conduct the calculation.

The default setting of parameters is listed in Table 21.1. As described in the previous section, the construction cost, efficiency, and auxiliary ratio are demonstrated with equations shown in Table 21.1. Labor cost must be changed by an equation reflecting capacity. However, this parameter suffered by the lack of salary payment data. Price of the primary forest biomass is adopted as the fuel price. The operation period is the same as that decided by FIT, i.e., 20 years.

21.2.5 Learning Effect

The term learning effect (hereafter, LE) is used to describe the function of cumulative production. LE in this paper refers to the process by which the technology cost declines as the technology is being developed and diffused. This characteristic is the

Table 21.1 The parameters for calculation of COE

	The committee	This study
Construction cost	0.3–0.4 (M JPY/kWh)	Eq. 21.4
Labor cost	700 (M JPY/kWh)	700 (M JPY/kWh)
Cost of fuel	7.5–17 (K JPY/t)	12 (K JPY/t)
Heating value	15 (MJ/kg)	15 (MJ/kg)
Efficiency	20 (%)	Eq. 21.2
Auxiliary ratio	13 (%)	Eq. 21.3
Capacity	5000 (kW)	100–5000 (kW)
Operation years	40 (years)	20 (years)
Discount rate	3 (%)	3 (%)

cost decline with a fixed ratio as cumulative production doubles [9]. This relation is shown in Eqs. 21.5 and 21.6:

$$C_{\mathrm{U}} = C_0 C_{\mathrm{um}}{}^{b} \tag{21.5}$$

$$\mathrm{PR} = 2^{b} \tag{21.6}$$

C_{U}: cost per unit
C_0: initial cost per unit
C_{um}: cumulative production amount
b: experience indicator
PR: progress ratio

PR refers to the "progress ratio," which shows the cost reduction rate as cumulative production becomes doubles. For example, if PR is 0.9, the unit cost becomes 90% of the original one.

This is an applicable measure for the energy technology. Biomass technology systems are different from other renewable energies, as they require fuel [9]. Junginger (2006) suggests that number of plants or the amount of generated electricity can be used as cumulative production in biomass technologies [10]. Junginger (2005) analyzed the biomass supply chain with the LE and reported that the wooden chip price from 1975 to 2003 becomes 87% as cumulative production doubled in Sweden [11]. Current study assumes an example is available for the Japanese wooden chip. To consider the LE, the data for the chip price and chip production from the Ministry of Agriculture, Forestry and Fisheries (MAFF) are used. However, as for the chip price, the primary material of fuel depends on the demand and supply balance significantly and fundamentally. In addition, Junginger (2005) described that the O&M cost for each plant is likely to decline as the number of constructed plants increases [11]. This is one of the motivations behind present work that investigates the LE for the fuel and O&M costs.

21.3 Major Findings

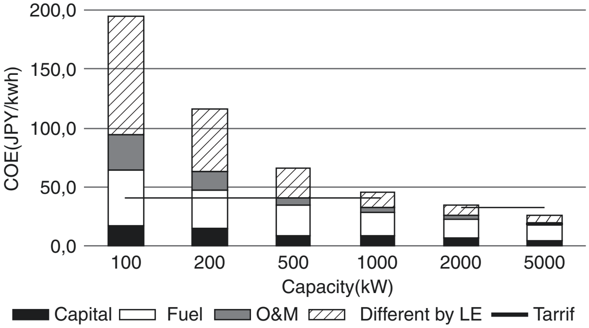
21.3.1 Cost of Electricity Analysis

Figure 21.2 shows the result of a COE analysis for each capacity. As present study targets the biomass sector, the tariff is either 32 or 40 JPY/kW [12].

The result when we change capacity at the range from 100 kW to 5000 kW is shown. From Fig. 21.2, it can be observed that the smaller the capacity, the higher the COE. In terms of tariff settings, the capacity for break-even point is estimated to be 1200 kW.

According to Fig. 21.2, the lower the capacity is, the higher the ratio of the O&M cost to the COE is. Current work assumes that O&M decreases with the LE and calculates the COE. The diagonal part indicates the cutoff due to the effect. Even though O&M cost declines because of the LE, small-capacity plants cannot expect to make a profit under the present tariff system.

Fig. 21.2 COE difference by learning effect



According to the chip price and production data from MAFF, it has not been proven that the cost decreases as chip production increases. In particular, after the implementation of FIT, the chip price becomes increasingly expensive. It is, therefore, our concern that the price remains high owing to the increase in demand.

21.3.2 Understanding the Profit Ratio

The equation below estimates the profit ratio with Eq. 21.7 based on the tariff and COE. Figure 21.3 compares the profit ratios to the estimation by the equation from the committee and this research with and without using LE.

$$\text{Profit} = \frac{\text{FIT} - \text{COE}}{\text{COE}} \times 100 \tag{21.7}$$

Profit: profit by the FIT (JPY/kWh)
FIT: tariff in FIT program (JPY/kWh)

According to Fig. 21.3, we can understand that the break-even point is between 500 kW and 1000 kW in present study when the LE is used, as well as from the estimation suggested by the committee. While in research that excludes the LE, the break-even point is estimated between 2000 kW and 5000 kW. However, the current FIT serves two tariffs that are lower and higher than those of the 2000 kW plants. Results of current work suggest that this discrepancy, if the plant that is over 2000 kW, has no consequence without the LE. If the LE is included, the plants can gain the profit from capacities in the range of 1000–2000 kW. We can suggest that another classification is needed for small plants where a capacity of less than 500 kW can arguably gain a profit.

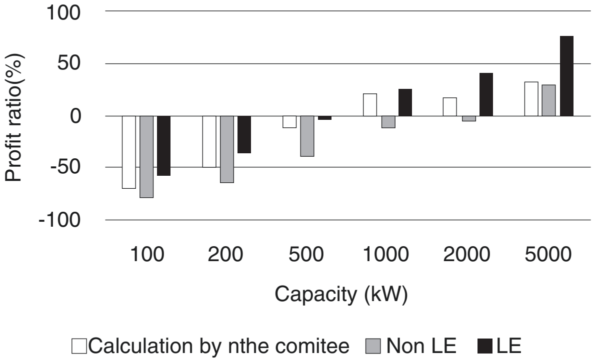


Fig. 21.3 Calculation by the Committee

21.3.3 Sensitivity Analysis

It is needed to investigate the reliability of the result shown above. Thus, sensitivity analysis by factor is conducted, and it investigates influences from each default parameter changing. Figure 21.4 shows the result of the sensitivity analysis for COE: (a) is for 100 kW and (b) is for 5000 kW. The range of each parameter is from plus to minus 10% on a standard plant, and standard condition is described at 0% plot. The reference plant uses the conditions described in the method adopted section. The parameters are power generation efficiency, auxiliary power ratio, capacity factor, annual capital cost, and cost of fuel.

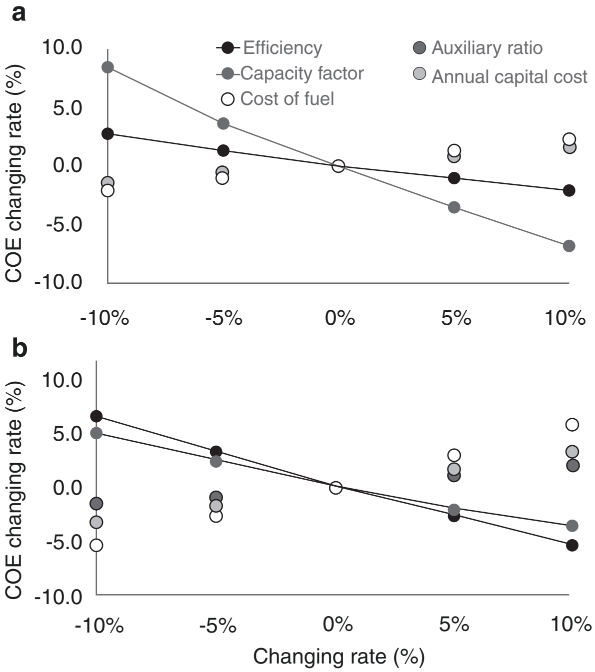
An explanation of choice is provided below. Efficiency and auxiliary ratio are the main two parameters that have relationship with biomass technology process or plant function. Capacity factor is influenced by the accidental troubles and maintenances. Economic reasons and finance situation give an impact to the annual capital cost. The cost of fuel probably is not the only effect for it also impacts the competitiveness with demand and supply of the material.

There are two common characteristics in both of Fig. 21.4(a), (b). One is that COE decreases as efficiency and capacity factor increase. Increasing efficiency and capacity means the function to generate power increases compared to the default condition and a denominator in Eq. 21.1 increase.

Another characteristic is that COE increases as auxiliary ratio, annual capital cost, and cost of fuel increase. Net power decreases when auxiliary ratio in the plant increases, because electricity consumption is more than default condition. Increasing annual capital and cost of fuel means numerator increases in LCOE equation. Thus, COE rises up.

The outstanding differences between these figures are efficiency and capacity factor. The larger the capacity scale, the more drastically efficiency changes the range of COE. It can be interpreted as follows: 5000 kW plant has higher efficiency

Fig. 21.4 Sensitivity analysis for COE. (**a**) 100 kW. (**b**) 5000 kW



than 100 kW, because efficiency is proportional logarithmically to capacity scale. Thus, Fig. 21.4(b) shows more influence by changing efficiency than (a). Figure 21.4(b) also indicates less effect by CF changing than (a), because CF does not depend on capacity scale, and the role of it is less effective relatively.

21.4 Conclusion

We analyzed the COE for small- and medium-scale biomass plants considering FIT and investigated the LE for O&M costs. Consequently, under the current FIT, the tariff is lower than the profit these plants can get, even though the LE is included. In addition, the current system cannot ensure profit via our profit ratio analysis for plants with a capacity of less than 500 kW. Therefore, a more specific classification for small plants is required in the next opportunity amendment to the current FIT. It is needed further to be considered such as small plants can act as CHP.

In the current work, only one stand-alone model plant was considered for investigation. The model plant targets boiler-turbine type of power generation; however, a study of COE based on gasification or ORC technology for different capacities is necessary. There are various plants in terms of plant scale and technology in reality, and we have to consider the variation. Therefore, additional investigation and analysis are required.

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Chapter 22
Renewable Energy Substitution Model and Environmental Preservation

Reza Nadimi and Koji Tokimatsu

22.1 Introduction

The Kyoto Protocol and the Paris agreement are two international treaties which concentrate on the renewable energy (RE) resources. The main purpose of the Paris Agreement indirectly focuses on global mobilization to reduce CO_2 emissions by means of renewables [1]. The Paris Agreement emphasizes on the role of RE resources to meet the following goals:

1. Mitigation of the greenhouse gas emissions.
2. Reduction on the global average temperature.
3. Mobilization of the financial supports to implement both previous goals.

On the other hand, carbon dioxide and sulfur dioxide emitted by fossil fuels into the environment result in global warming and acid rain [2]. Increasing the share of renewables in the energy mix program of countries will decline the burden of fossil fuels in the energy production system [20]. Estimation of the energy consumption prepares a suitable vision for decisionmakers in the energy production planning system to maximize the renewables share in the energy mix program.

22.2 Literature Review

Based on the World Energy Statistics in 2014, the share of renewable versus nonrenewable energy (NRE) resources was 14.1% and 85.9%, respectively [3], which the share of NRE resources consists of oil (31.3%), coal family (28.6%), natural gas

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(21.2%), and nuclear (4.8%). On the one hand, the excessive use of NRE resources speeds up the natural resource depletion. On the other hand, it raises the greenhouse gas emissions and has a negative impact on the environment.

Forecasting of the energy consumption is one of the key elements for decision-makers of the energy system. Appropriate decision about the share of RE resources in the energy mix program has a significant contribution to decrease the negative impact of NRE resources on the environment. Usually econometric approaches [4–6] are applied to the load forecasting, which establishes a decent vision for the energy programming. Another well-known method for the load estimation is to use diffusion and substitution models. These models consider the growth rate of the market and technology change in the estimation process [7, 8].

Substitution Models: Fisher [9] introduced a simple technological changing model, in which substitution was specified by the proportion of the new technology to the old one. Sharif and Kabir [10] conducted a research to generalize the Fisher technological substitution model. In this regard, they added two factors (delay coefficient and delay factor) in the Fisher model to moderate the forecasting model from optimistic to pessimistic state. Meade [11] developed a statistical model to consider the technological substitution process. The latest observation was used to update the model. The model utilized the Kalman filter technique to estimate the model parameters.

Diffusion Models: Hun and Lee [12] investigated the growth rate pattern of five RE technologies. A price function and diffusion model were applied as a stimulator to decrease the uncertainty of renewables and load forecasting. Meade and Islam [13] modeled the use of renewables in the electricity generation system to utilize the trajectory of price and export/import security of fossil fuels for the future and environmental impact. They classified the growth rate of renewables in terms of 4 groups for 14 European countries. Additionally, their findings implied that the fossil fuel price changes did not remark an influence on the variation of RE usage. Kumar and Agarwala [14] introduced several innovations in renewables, energy efficiency, and incentive schemes to increase the diffusion rate of renewables in India. They proposed an integrated approach to diffuse the RE technologies, which consist of conversion, cost, technology components, availability of resources, and policy. They found that a great hamper for diffusion of renewables is the lack of investment.

Inherent uncertainty of the RE resources is one of the fundamental factors in the load forecasting models. Climatic change, wind, sun, water shortage, and cultivation land under biomass are some of the sources of uncertainty that should be considered within the modeling process. This study utilizes the Bayesian inference and PRNG method to model the aforementioned uncertainty. Therefore, the prior, $P(\Lambda)$, and likelihood, $P(x|\Lambda)$, probabilities are calculated to update the posterior probability, $P(\Lambda|x)$, based on the latest information as follows [15]:

$$P\left(\Lambda \mid x\right) = P\left(\Lambda\right) \times \frac{P\left(x \mid \Lambda\right)}{P\left(x\right)} \quad \text{Posterior} = \text{Prior} \times \text{Likelihood} \tag{22.1}$$

where $p(x)$ is the probability of evidence x regardless of any other information. The denominator of the equation above normalizes the posterior probability. This paper considers the expected value of the posterior distribution as an estimation value for the RE resources.

22.3 Methodology

The current study proposes a framework to estimate the growth rate of RE compared with NRE resources. It is necessary to consider the inherent uncertainty of the RE resources within the estimation of the RE resources' growth rate. This paper applies Bayesian inference ([15]) and the PRNG algorithm[1] [16] to reduce the uncertainty. Then it simulates the variation of electricity generation through RE resources as much as possible. Indeed, the PRNGs are applied to embed a potential uncertainty of the renewables into the model. Then, the proposed model tries to estimate the substitution of the renewables in the presence of uncertainty.

22.3.1 Construction of the Proposed Model

Figure 22.1 shows the conceptual framework of the proposed model. To estimate electric power consumption for each country, a linear trend model [17] is fitted to the total electric power consumption (y). The time horizon of this study is the end of the year 2030.

Current research assumes that investment or any decision about RE resources will be conducted within a 5-year period (or midterm decision). Therefore, the RE data (x) that belong to the latest 5-year period are kept to calculate the likelihood function of the Bayesian inference. Additionally, the PRNG algorithm is utilized to deal with the natural uncertainty in the renewables (shortage of water, sun, wind, and climate change). Based on the latest 5 years' data that belong to the RE resources, 30 pseudorandom numbers of the beta distribution are generated. From mathematical insight, a simple substitution model describes the rate of replacement into the two complementary events in which the replacement rate varies between zero and one. The domain of the beta distribution is also changed in similar range. Therefore, the beta distribution is used to generate random numbers.

Advancement and development of RE technologies during current decades bring about an increment of renewable energy shares in the energy mix of countries. The historical data of the renewables in different countries illustrates a trend of progress for each country, while the latest data provides more information about renewables in a country. Therefore, using all historical data with same weight to forecast the

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[1] The PRNG is an algorithm to generate a sequence of numbers whose properties are approximately similar to the properties of sequences of random numbers.

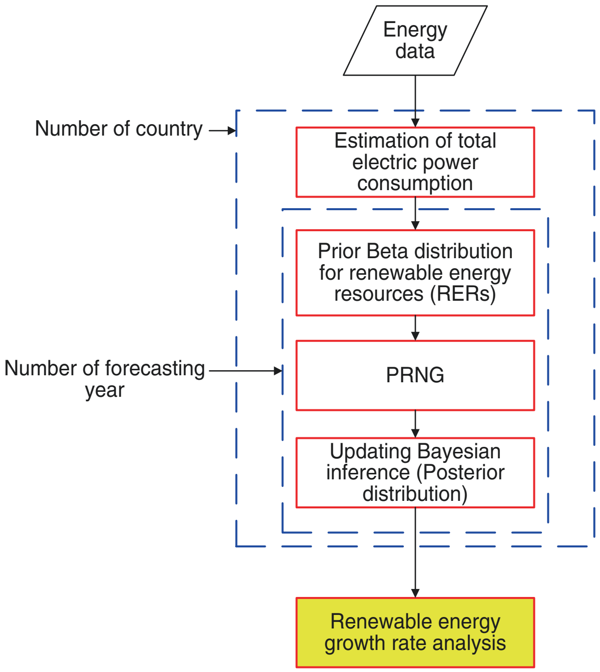


Fig. 22.1 Conceptual framework of the proposed model

share of renewable energy provides inappropriate results. In other words, usually the old data gives less information compared with current data. Therefore, to decrease the impact of the old data (outlier or outdated data), different weights (*w*) are assigned to observations, and then, the most influential data is selected based on their pertinent cumulative weights. The cutoff point is defined by cumulative weight (≥0.8) to separate the less influential data from other data. The weighting factor prevents from biasing the prior distribution. Therefore, at the first step, different weights are calculated as follows:

$$w_i = \frac{x_i}{\sum_{i=1}^{m} x_i} \quad s.t. \; \sum_{n}^{i=1} w_i \geq 0.80, \; n < m \tag{22.2}$$

where n implies the total historical data and m points out the number of historical data by which the cumulative weight of data reaches the cutoff point. By moving forward in time, the value of m increases. This technique excludes the less important previous RE data through a threshold value (80% of the cumulative weight). Therefore, 80% of the recent RE data is used to generate the prior function from the beta distribution. Afterward, the posterior distribution is updated by product of the prior distribution value in the likelihood distribution values. Finally, the RE growth rate within the estimation period (2014–2030) is analyzed to consider the level of RE substitution instead of NRE. Figure 22.2 depicts the ideal substitution model of the RE against NRE, in which the fossil fuel resources are substituted by RE resources.

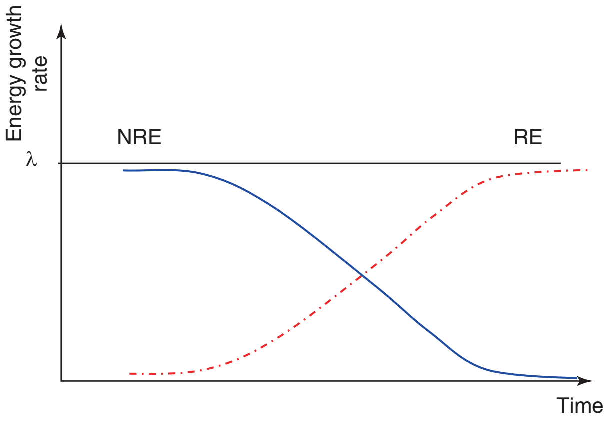


Fig. 22.2 Schematic representation of the ideal substitution model

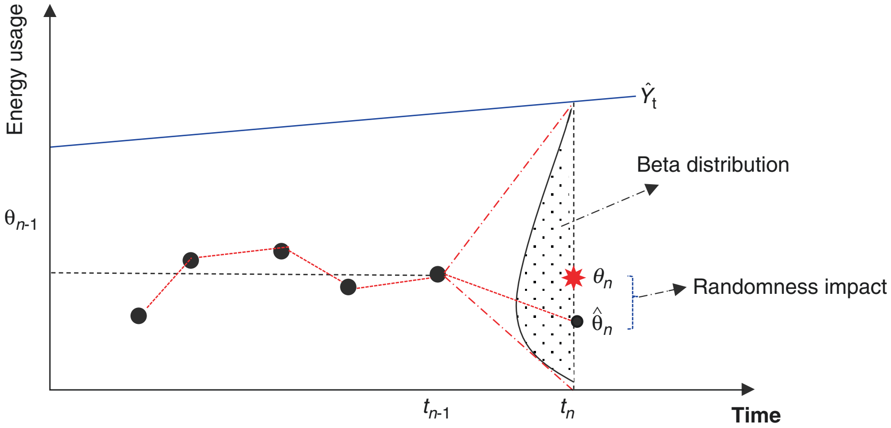


Fig. 22.3 Substitution model of renewables

The total energy growth rate (λ) is fulfilled by both RE and NRE. The intrinsic uncertainty of RE resources changes the priority from the RE to the fossil fuel resources and postpones the substitution process. On the other hand, fossil fuel depletion, as well as their impacts on the environment, accelerates the aforementioned process.

Therefore, the ideal status of the sigmoid substitution function, ($\lambda_{\text{Sigmoid\_RE}}/(1 - \lambda_{\text{Sigmoid\_NRE}})$), is transformed into $\lambda = \lambda_{\text{Sigmoid\_RE}} + \lambda_{\text{Sigmoid\_NRE}}$, where $\lambda_{\text{Sigmoid\_RE}}$ (or $\lambda_{\text{Sigmoid\_NRE}}$) indicates the energy growth rate under renewables (or nonrenewables). Figure 22.3 represents an overview of the applying Bayesian inference and PRNG method to extract the amount of energy consumption in the year t_n. At the first step, total energy consumption is forecasted for the year t_n by a linear trend model in which its explanation is given below. All historical renewable data is normalized by dividing into the forecasted value. In fact, the forecasted value is considered the maximum (or upper bound) amount of renewables generated in the year t_n. (In this case, the substitution is completely carried out). All selected historical data based on the Eq. (22.2) are used to estimate the prior distribution. The last 5 years' data are applied to estimate the likelihood function. Although by multiplying the likelihood and prior distribution, the posterior distribution parameters (θ_n) are achieved, the influence of uncertainty has not been considered yet. Then, the PRNG method is used to generate a set of random numbers and recalculate the parameters of the posterior distribution in the presence of uncertainty ($\hat{\theta}_n$). However, the value of λ is changed over time and is calculated by the linear trend model (Fig. 22.3). Mathematical steps to conduct the conceptual framework are given as follows:

First: According to Fig. 22.3, a linear trend model is conducted to obtain $\hat{Y}_t$, for each country, where $t = 2014,\ldots,2030$ (17 years). Electric power consumption data contains 44 years (1970–2013) except for the countries of the Soviet Union, Namibia, Cambodia, and Mongolia in which their data are available just after 1990.

$$\hat{Y}_t = u + v \times \text{index}(t),\ t = 2014,..,2030 \tag{22.3}$$

where u and v are the intercept and slope of the function. The "index (t)" refers to the number of observation and estimation data contributed in the linear trend model. For example, if all data (1970 till 2013) are used in the estimation of the linear trend line, then index ($t = 2014$) will be 45, because in this case, the starting point is 1970 and so on. The estimation values are considered as an upper bound for the electricity generation through the RE resources.

Second: A beta distribution associated with the prior probability is specified based on the percent of the RE data which is available from the years 1990 to 2013. All selected RE data through Eq. (22.2) are scaled up in terms of the estimated electric power data, $\hat{Y}_t$, as follows:

$$\theta_i = \frac{x_i}{\hat{Y}_t}\ \ i = t_1, t_2, \ldots, t_{n-1} \tag{22.4}$$

where θ_i identifies the growth rate of the RE resources and ($n-1$) represents the number of data selected through Eq. (22.2).

The best beta distribution function with shape and scale parameters of (α_0, β_0) is fitted to the selected growth rate data as follows:

$$\mathrm{E}(\theta_t) = \frac{\alpha_0}{\alpha_0 + \beta_0} \tag{22.5}$$

$$\mathrm{Var}(\theta_t) = \frac{\alpha_0 \beta_0}{(\alpha_0 + \beta_0)^2 (\alpha_0 + \beta_0 + 1)} \tag{22.6}$$

where E(..) and Var (..) represent the expected value and variance of the selected growth rate data, respectively. Substitution is completed when the growth rate of the RE exceeds 0.99%. In contrast, incomplete substitution occurred when the growth rate of the RE is less than 0.005. Therefore, 0.005 value is considered as the lowest growth rate for a country in which its RE share in the energy mix program is close to zero (less than 0.005). This assumption is launched in order to handle beta distribution. Mongolia, Cambodia, the United Arab Emirates, Oman, Qatar, Saudi Arabia, Kuwait, Bahrain, Libya, Botswana, Turkmenistan, Malta, and Cyprus are countries with the aforementioned issue.

Third: To calculate the beta likelihood function at time *t*, the information of the last 5 years' growth data are utilized the same as the second step. Then, a set of random numbers (r_i) equals to $w = 30$ are generated by PRNG algorithm from the beta likelihood distribution with parameters of (α_L, β_L) in which the subscript *L* stands for likelihood distribution. These numbers change the expected value and variance of the beta likelihood function to simulate the inherent uncertainty in the energy mix program (randomness impact in Fig. 22.3).

Fourth: For each year, the posterior distribution parameters are calculated as follows:

$$\alpha_p = \alpha_0 + \sum_{w=30}^{i=1} r_i \tag{22.7}$$

$$\beta_p = \beta_0 + w - \sum_{w=30}^{i=1} x_i \tag{22.8}$$

where the subscript *p* stands for posterior distribution in (α_p, β_p). The *q* implies to the number of the random number in the PRNG algorithm. Additionally, the pair of (α_0, β_0) points out the parameters of the prior distribution which was explained in the second step.

Fifth: The expected value of the posterior distribution function is used to return the scaled value of the growth rate data to the estimated RE data as follows:

$$\hat{x}_t = \hat{Y}_t \times \frac{\alpha_p}{\alpha_p + \beta_p},\ t = 2014,\ldots,2030. \tag{22.9}$$

The above Bayesian process generates the growth rate of RE for each country. Through this growth rate, the RE proportion is determined in terms of the total estimated electric power consumption. As a result, the share of the fossil fuel resources to generate electricity is achieved. Additionally, the substitution level of RE against NRE will be measured by which the amount of resource savings and the environmental preservation is calculated.

22.3.2 Data

Electricity consumption data (GWh) belong to 112 countries was collected for 44 years (1970–2013) [18], while their RE data (GWh) was gathered for the period of 24 years (1990–2013) [18]. Renewable energy resources include industrial and municipal waste, biogas, liquid biofuels, primary solid biofuels, geothermal, hydro, tide, wave, ocean, wind, biodiesels, solar thermal and PV. Moreover, CO_2 emissions data was collected for 112 countries from the year 1990–2013 [19].

22.4 Results and Discussion

Total electric power consumption for each country was estimated, and a linear trend line was calculated for all countries. The number of observation data used in the forecasting process was determined in a manner to achieve positive values for the parameters of u and v. Thus, a different starting point or index (t) value was obtained for each country. Appendix I summarizes the final results of the first step for all countries. At the next step, these parameters and index (t) were used to forecast the total electric power consumption until the year 2030. The output of this part was applied as an upper bound for electric power consumption for each country, in which the maximum amount of RE consumption was limited to the upper bound. Figure 22.4 depicts the total electric power consumption for 112 countries since the year 1990–2030. Total electric power consumption from year 2013–2030 was

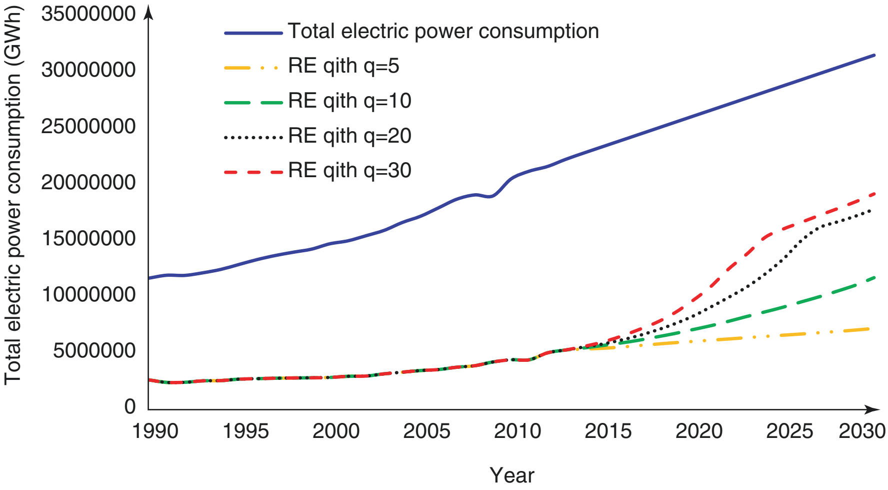


Fig. 22.4 Total electric power consumption

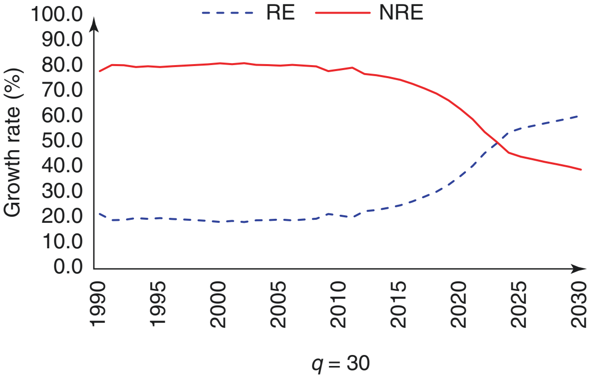


Fig. 22.5 Substitution model of RE instead of NRE

calculated based on the linear trend model. According to the linear trend model for all countries, total electric power consumption has reached 31,415,263 GWh in the year 2030.

The rest of the proposed steps provides the share of the renewable energy resources in the total electric power consumption. According to Fig. 22.4 for the year 2013, the RE proportion is 23.2% out of the total electric power consumption (22,141,016 GWh). Figure 22.5 shows 54.0% of the total electric power consumption (28,149,014 GWh) in the year 2024 will be supplied by the RE resources ($q = 30$). Based on the statistics, the growth rate of RE will decrease by current RE technologies from the year 2026 until the end of 2030. In other words, by decreasing the number of PRNGs (q), estimation of the RE data will be affected by the prior distribution. Therefore, the previous data selected by Eq. (22.2) had more impact on the estimation value of the RE data.

In contrast, increase in the number of PRNGs causes the recent RE data dominates the estimation of the posterior distribution and influences the RE amount. Moreover, increase or decrease in the number of PRNGs influences the RE development among 112 countries and, finally, changes the substitution model.

The value of q determines how much uncertainty is acceptable in the model. By decreasing the q value, the model inclines toward historical data (prior) rather than current data (likelihood). In contrast, icreasing the value of q illustrates that the electricity generation through renewables in a country will follow based on the last 5 years' data (because it was supposed any investment in the renewable energy sectors follows midterm periods). Therefore, if $q = 10$ then RE and NRE curves for the substitution model do not cut each other until the year 2030 (Fig. 22.6). Additionally, the rate of electricity consumption generated by NRE will be greater than RE, when the q value is equal to 5. Thus in this case, two general sources of energy, RE and NRE, will not meet each other in the substitution model. Generally, from the economic point of view, increase in the value of q equals to the investment on RE technologies. In other words, by investment of the RE technologies, uncertainty decreases through the enhancement of efficiency and number of RE technologies. Therefore, the value of q is a function of investment on RE technologies.

Fig. 22.6 Substitution model of RE ($q = 10$)

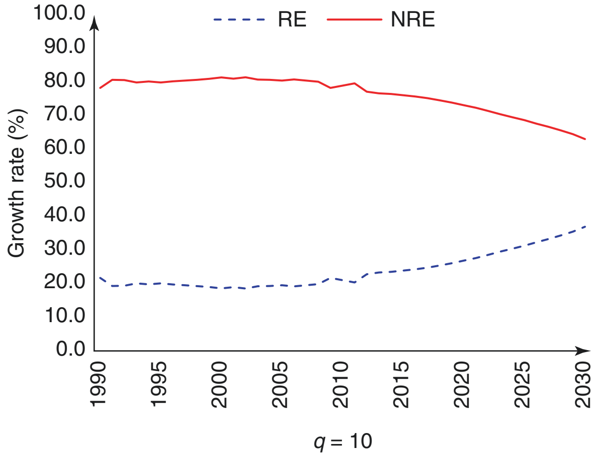
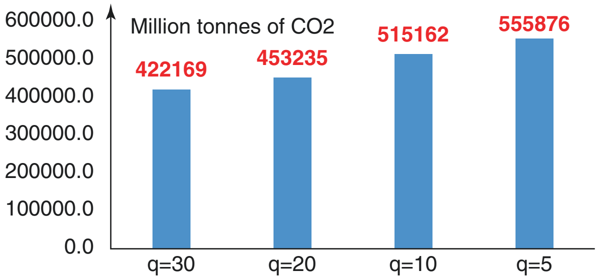


Fig. 22.7 Amount of carbon dioxide emission



The rate of emitted carbon dioxide (CO_2) emissions into the environment depends on the fuel types. To analyze emissions through fuels, it needs to compare the amount of CO_2 emitted per unit of energy output. This paper applies the regression analysis to find the relationship between CO_2 emission and the amount of NRE consumption for the electric power consumption.

According to the regression analysis, the following linear regression was obtained by fitting the model to the data belongs to the years 1990–2013.

$$\mathrm{CO}_2\ \text{emission} = 5570.7 + 0.0013 \times \text{NRE} \tag{22.10}$$

in which CO_2 emission was measured by million tonnes of CO_2. The coefficient of determination, R^2, achieved 0.98, which demonstrates how well the model fits to the observed data (NRE, CO_2 emissions). All four types of substitution model results were considered in terms of CO_2 emissions and environmental preservation. Figure 22.7 depicts how much of CO_2 emissions are reduced by different types of substitution models. It is obvious that increase in the substitution of RE instead of NRE brings about reduction in the CO_2 emissions.

22.5 Conclusion

A substitution model was proposed in this research to generate electricity from renewables instead of nonrenewable energy resources. Electric power consumption was forecasted based on a linear trend model in a way the pertinent coefficients of the model obtained positive value. The outcomes of the linear trend model were used as an upper level for the electric power generation through renewables. Bayesian inference and PRNG method were applied to estimate the contribution of the RE resources in the total electric power consumption. The proposed substitution model was analyzed through changing the number of PRNGs in the four defined scenarios. The results of the four scenarios manifested that by increasing the amount of q, substitution process is accelerated, while the CO_2 emissions is reduced. From the economic perspective, the value of q depends on the investment on RE technologies. This investment may be handled through promotion of the efficiency and/or the number of RE technologies. Based on the proposed model, if $q = 30$, then the substitution model would start from the year 2024 and the level of CO_2 emissions would equal to 422168.9 million tonnes of CO_2. In contrast, by decreasing the value of q, the substitution period was postponed. For instance, by choosing $q = 20$, the substitution process did not completely perform until the end of 2030.

Appendix: Parameters of the Linear Trend Model and Starting Year for Each Country

	Parameters		Starting		Parameters		Starting
Country name	u	v	point	Country name	u	v	point
Australia	37025.5	4991.5	1970	Cyprus	9.5	85.3	1972
Austria	21612.5	1177.4	1970	Georgia	5987.8	212.5	1995
Belgium	31231.5	1548.3	1970	Kazakhstan	40349.0	2318.1	1995
Canada	227925.8	8757.8	1970	Latvia	4401.7	127.0	1993
Chile	646.2	1960.0	1981	Lithuania	8970.6	107.2	1993
Czech Republic	44719.0	624.5	1976	Malta	102.2	50.0	1971
Denmark	31415.0	190.1	1976	Romania	47003.0	243.5	1996
Estonia	6541.0	70.4	1990	Russia	707373.0	10568.0	1993
Finland	64241.0	1171.8	1990	Serbia	29993.0	189.1	2004
France	366221.0	6156.0	1990	Tajikistan	23747.0	274.1	1994
Germany	371972.3	5628.0	1970	Turkmenistan	5744.6	269.8	1990
Greece	7087.8	1321.3	1970	Ukraine	148404.0	486.6	1994
Hungary	22339.8	427.9	1970	Uzbekistan	42834.0	248.6	1992
Iceland	1240.4	2336.6	1989	Algeria	191.2	1030.6	1977

Country name	Parameters		Starting point	Country name	Parameters		Starting point
	u	v			u	v	
Ireland	3021.5	584.9	1970	Angola	121.7	1674.6	2002
Israel	562.1	1358.6	1973	Botswana	87.5	105.8	1981
Italy	238657.0	4787.3	1990	Cameroon	209.9	196.2	1971
Japan	908349.0	91.2	1990	Ethiopia	697.1	1028.2	2000
Luxembourg	3034.3	118.7	1970	Gabon	179.2	33.4	1971
Mexico	5513.0	5640.1	1971	Ghana	28.7	466.1	1972
Netherlands	39069.1	1949.8	1970	Kenya	590.7	130.1	1971
New Zealand	13607.2	718.2	1970	Libya	231.2	548.1	1977
Norway	36060.0	4994.5	1970	Mauritius	11.7	87.9	1983
Poland	83089.9	1516.4	1970	Morocco	100.0	670.0	1976
Portugal	2185.5	1193.7	1970	Mozambique	1349.0	1875.1	1996
Slovenia	9592.2	208.4	1990	Namibia	1087.7	118.2	1991
Spain	128941.0	6909.8	1990	Nigeria	231.8	530.5	1974
Sweden	126470.0	513.9	1983	Senegal	14.9	60.3	1975
Switzerland	28675.8	901.8	1970	South Africa	50816.0	4818.9	1971
Turkey	46.8	6092.3	1982	Sudan	249.3	979.6	2003
United Kingdom	231957.0	3496.8	1970	Togo	35.9	17.4	1971
United States	2000000.0	67849.0	1970	Tunisia	86.0	376.0	1976
Argentina	6980.1	2461.1	1971	Zambia	4468.8	183.8	1971
Brazil	670893.0	47010.0	1990	Zimbabwe	6329.8	100.1	1971
Colombia	134459.0	3961.9	1990	Bahrain	87.2	706.1	1979
Costa Rica	1790.4	2209.0	1984	Iraq	3827.8	817.4	1971
Cuba	5862.7	229.3	1971	Jordan	233.0	383.7	1983
Dominican Republic	157.6	497.3	1983	Kuwait	572.3	1392.2	1977
El Salvador	66.2	130.9	1973	Lebanon	96.6	408.3	1979
Ecuador	4966.6	878.6	1997	Oman	259.1	805.8	1990
Haiti	136.6	9.2	1971	Qatar	1105.1	1686.5	1996
Honduras	2685.3	423.6	1990	Saudi Arabia	4179.4	7216.9	1982
Jamaica	1020.3	101.3	1971	United Arab Emirates	1415.6	4335.4	1991
Nicaragua	896.4	101.7	1991	Bangladesh	627.2	1963.1	1993
Panama	1686.1	235.4	1991	Cambodia	17.1	254.0	2002
Paraguay	112858.0	1165.2	1990	India	1876.7	24690.0	1981
Peru	7964.0	1282.3	1992	Indonesia	2622.5	6569.8	1988
Trinidad and Tobago	118.1	184.6	1971	Malaysia	495.4	4346.4	1986
Uruguay	13765.0	774.6	1990	Mongolia	2471.5	48.4	1985
Albania	1790.9	711.9	1992	Nepal	62.7	159.8	1988
Armenia	3431.5	111.9	1995	Pakistan	152.2	2325.5	1977
Azerbaijan	16257.0	78.1	1990	Philippines	2116.2	1312.2	1971
Belarus	29223.0	202.4	1993	Singapore	165.2	1312.7	1978

Country name	Parameters		Starting point	Country name	Parameters		Starting point
	u	v			u	v	
Bosnia and Herzegovina	2549.3	486.7	1992	Sri Lanka	230.2	295.6	1981
Bulgaria	28932.0	174.5	1970	Thailand	2494.6	5282.6	1983
Croatia	9971.6	298.5	1990	China	54716.0	238844.0	1995

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Chapter 23
Recent Progress on Soft Transducers for Sensor Networks

Seiki Chiba, Mikio Waki, Koji Fujita, Zheqiang Song, Kazuhiro Ohyama, and Shijie Zhu

23.1 Introduction

A very simple structure, a DE is comprised of a polymer film (elastomer) sandwiched between two electrodes made of a flexible and elastic material [1, 2]. Applying a voltage difference between the two electrodes causes a compression in the horizontal direction and a stretching along the surface [2] (see Fig. 23.1).

DE elements can be used to make a variety of devices, such as linear actuators, diaphragm actuators for fluid pumps, and actuator arrays [2, 3]. Additionally, its low cost, light weight, softness, high efficiency, and quietness make the actuator suitable for robots, motors, speakers, and smart materials.

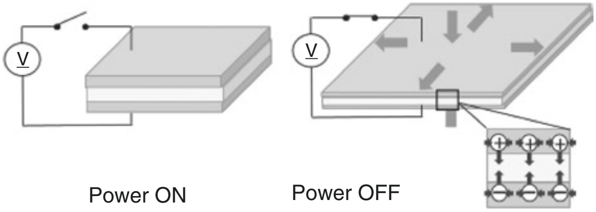

Fig. 23.1 Principle of DE actuator

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The DE actuator features a fast speed of response (over 100,000 Hz has been demonstrated for small strains), with a high strain rate (up to 600%) [4, 5]. A DE having only 0.1 g of DE materials can lift a weight of 2 kg using carbon system electrodes [4]. These qualities make it suitable for use within robotic hands or feet.

DEs furthermore have applications beyond only actuators; they can be applied to new functional devices such as compliant sensors and electrical power generators [2–16]. This paper discusses the potential for sensor networks and how they might be used to create the basis of a low-carbon economy (LCE) society. If any of these opportunities is to be commercially successful, it will have to leverage the DE's advantages over conventional technologies.

23.2 Dielectric Elastomer Sensors

A direct proportionality exists between the change in the capacitance and elongation of DE actuators (see Fig. 23.2); they can be used for pressure sensors and position sensors [17].

This relation can be expressed

$$C = \varepsilon S / d \tag{23.1}$$

where C is the capacitance of the DE (F), ε is the dielectric constant of the polymer film (F/M), S is the active polymer area (m^2), and d is the thickness of the polymer (m).

Application of DE sensors with DEG will be discussed in Sect. 23.4.

23.3 Dielectric Elastomer Generators

The principle of operation in the generator mode is the transformation of mechanical energy into electrical energy by deformation of the DE. Functionally this mode of operation resembles piezoelectricity, but its power generation mechanism is

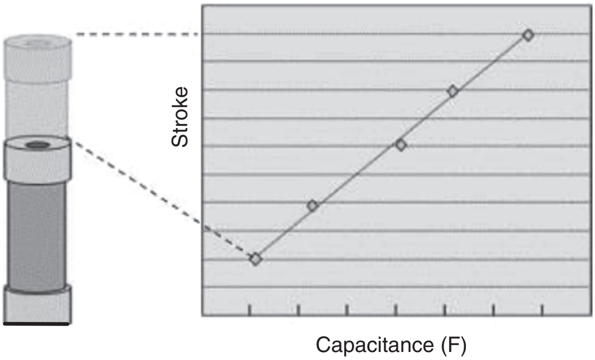


Fig. 23.2 Linear relation between capacitance and stroke of actuator

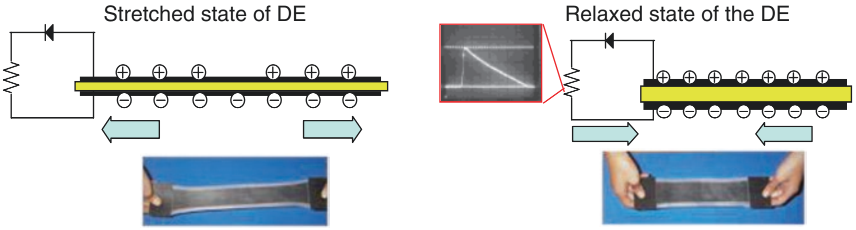


Fig. 23.3 Operating principle of dielectric elastomer power generation; the DE generator is basically a stretchable capacitor. If a charge is applied to the DE generator in the stretched state, then work done by the contracting elastomer is converted into electrical energy (as illustrated by the voltage across the resistor in the right illustration)

fundamentally different [18]. While piezoelectric devices require higher-frequency impulsive mechanical forces to generate electrical power, DEs can generate power from even slow changes in its shape [18]. Moreover, DEs exceed piezoelectricity in the amount of electrical energy generated on a per mass basis and the efficiency of conversion from mechanical to electrical energy [19–21]. Figure 23.3 shows the operating principle of DE power generation.

A typical energy harvesting cycle is as follows:

1. Application of mechanical energy to a DE to stretch it causes compression in thickness and expansion of the surface area.
2. A voltage is applied to the membrane. The applied energy is produced and stored on the polymer as an electric charge.
3. The stretching forces are removed. The recovery force of the DE acts to restore the original thickness and to decrease the in-plane area. At this time, the electric charge is pushed out to the electrode direction. This change in electric charge increases the voltage difference, resulting in an increase of electrostatic energy.

Application of DE generator for IoT networks will be discussed in Sect. 23.5.

23.4 Application of DE Sensors with DE Generators

As sensors, DEs can be used in all of the same configurations as actuators, as well as generators. The smart shape robots or care equipment seen in science fiction movies may appear in the very near future [22]. We are advancing a practical use study using DE artificial muscle as a sensor to analyze the movement of the human body. DE sensors can also be used in combination with DEGs to continuously send information wirelessly to doctors and nurses. For example, if the body temperature of an elderly person living alone drops, the air conditioner can automatically raise the room temperature, and the doctors and nurses can be notified. The DE sensors for this kind of system will be discussed in the next section**.** Industrial sensors are discussed in Sect. 23.4.2.

23.4.1 DE Medical Sensors

Ribbon-shaped actuators with a sensor function can be used to measure force or pressure as well as motion at the same time. Photo 23.1 shows the ribbon form actuators for rehabilitation [22, 23].

This actuator can assist human motion while simultaneously working as a motion feedback sensor. We hope that it may be useful for smart rehabilitation equipment for hands, legs, and fingers. Such equipment may be used to precisely evaluate a recovery. The DE was made from acrylic elastomer with a carbon black electrode.

The capability to gauge the timing and depth of breathing with a PC using a breathing sensor was also developed [24] (see Photo 23.2).

Power for the drive is supplied from the PC's USB, thus making this setup easily portable as well as capable of remote patient monitoring. A study into the utilization of this sensor system for dementia prevention is already underway at some Japanese universities. Additional applications to sports training, mental training, and medical treatment are also possible.

23.4.2 DE Industrial Sensors

Major industries like agriculture, fishery, and forestry have begun to turn to IoT using wireless networks to increase productivity and value. Often used outdoors, these systems must be designed with great consideration for the source and efficiency of their electricity supply. A DE capable of generating electricity from a variety of energy sources can be used to power DE sensor systems.

As an illustration, in the world of fish farming where global demand increases yearly, the size of fish tanks is increasing along with a growing reliance on automation to reduce labor costs (see Fig. 23.4). That requires a variety of real-time systems and actions such as automatic feeding machinery, net cleaning systems, and environmental monitoring, for which the combination of DE sensors and DEGs could be invaluable for wireless systems. We will discuss the development of DEGs to back up DE sensors in Sect. 23.5.

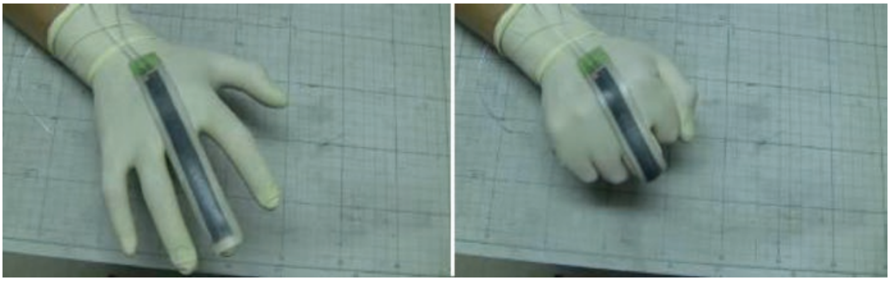


Photo 23.1 Ribbon form actuators for rehabilitation purpose

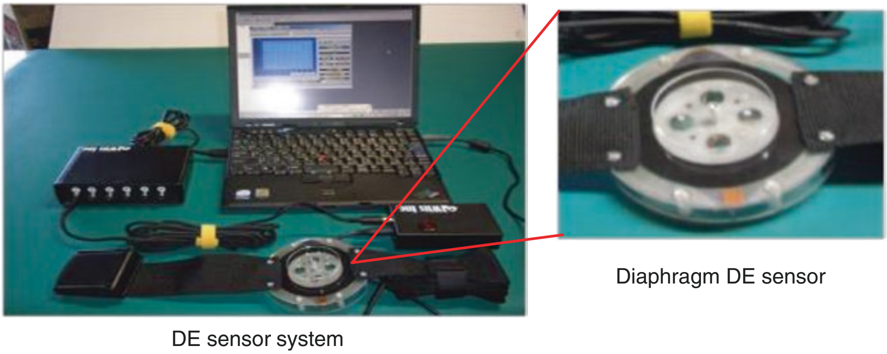


Photo 23.2 DE sensor system for dementia prevention

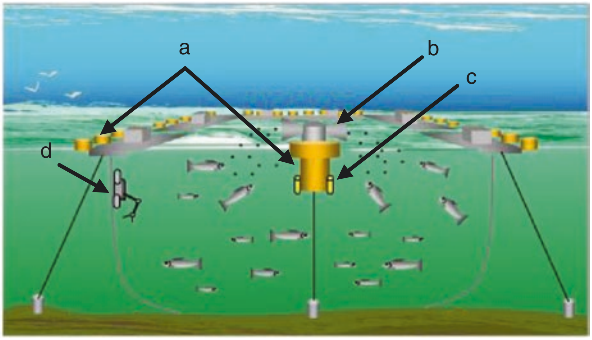


Fig. 23.4 Image of fish farming system. (**a**) DE generators. (**b**) Automatic feeding machinery using DE actuators and sensors. (**c**) Environmental monitoring systems using DE sensors. (**d**) Cleaning Robots using DE actuators and sensors

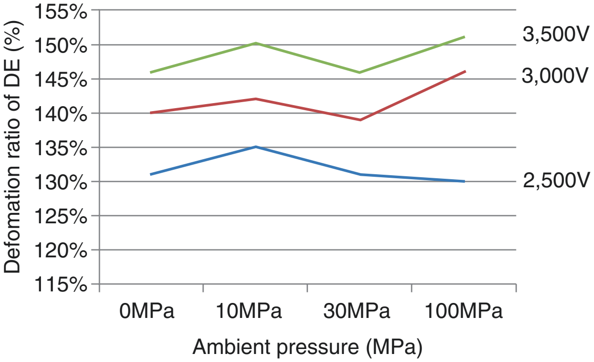
Recently organic farmers have been using LED lights emitting insect-repelling lights or smells and also using drones to check growth or prevent theft. For such systems, dielectric elastomers would be ideal because of their electricity supply and wireless systems.

Large-scale disasters such as volcanoes, earthquakes, and tsunamis occur frequently around the world, and dielectric elastomers are being investigated for their capabilities to aid observation and mitigation of disasters.

DE sensors can quantify three-dimensional shape changes and can measure complex deformations, so they can be used to measure signs of collapse in buildings, tunnels, and bridge piers. By connecting these via wireless systems to the Internet, remote management and analysis of data and prediction of failure become possible.

In a recent experiment, we have verified [25] that the DE can maintain good operational characteristics even in an ultrahigh pressure environment by showing that the electroactive strain response to an applied voltage was unaffected by externally applied pressures of up to 100 MPa. Figure 23.5 shows the deformation ratio of the DE at different ambient pressures and applied voltages [25]. It demonstrates that DEs could be used as sensors in deep-sea conditions to understand the earth's weather system.

Fig. 23.5 Deformation ratio of DE at different ambient pressures and applied voltages



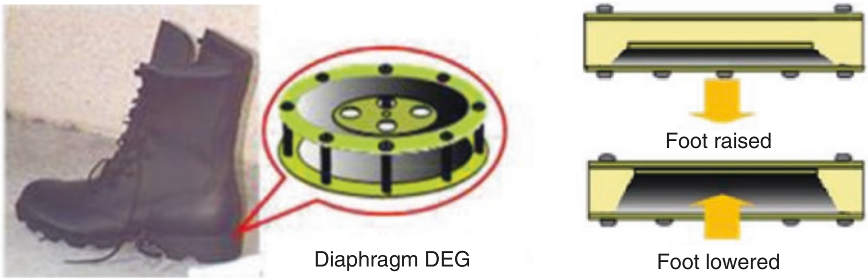


Fig. 23.6 Shoe generator

23.5 Application of DE Generators

In a power generation experiment, a thin DE film (20 cm long × 5 cm wide, weight about 0.4 g) attached to a human arm was able to generate 50 mJ of electrical energy with one arm movement [23]. It is also possible to make DEs generate electricity putting them along the arm and the chest.

Furthermore, in an experiment using different power generation equipment, DE film attached to the bottom of a shoe was confirmed to generate electricity from the distortion of the artificial muscle during walking (see Fig. 23.6). For each step of an adult male at a speed of one step per second, a single shoe was able to produce about 1 W of electrical power [23].

This result shows that human movements can be utilized to obtain sufficient electrical power to recharge batteries for mobile telephones and similar devices. In addition, electrical energy from the movements of animals could be used to construct livestock management systems. Other applications of animal-generated energy being investigated include scientific surveys of ecosystems of migratory birds and fish.

In an experiment using a DE diaphragm actuator, electrical power output of about 0.15 W was obtained by pressing the center of a roughly 0.1 g, 8 cm diameter

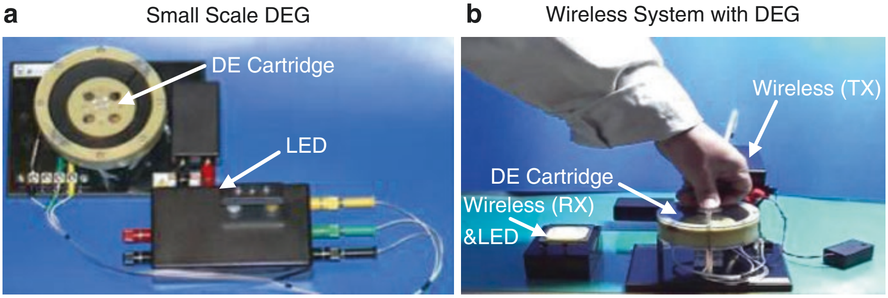


Photo 23.3 Small-scale power generation device and LED controlled by wireless signals. (**a**) Small Scale DEG. (**b**) Wireless System with DEG

DE a few millimeters once per second [6] (see Photo 23.3). Using the same equipment, the electrical power generated was able to illuminate six LEDs. This combined with a wireless system enabled a device to be turned off and on from a remote location.

In such ways, DE generators can supply electrical power only when mechanical energy is obtained, and it is possible to simultaneously act as a switch that detects power sources and motion. Consequently, it may be possible to easily create wireless networks, with simple components that do not require batteries [6].

23.5.1 DE Wave Generators to Assist Worldwide Sensor Networks

In recent years, global warming and accompanying abnormal weather patterns have begun to impact our daily lives. To protect ourselves from the myriad of possible threats created by climate change, it is essential to thoroughly understand the current situation and how the global environment is changing. The monitoring of the global environment has been done by various countries individually. However, monitoring environmental changes on a global scale necessitates building wide-ranging sensor networks. A major impediment toward that, however, is that currently no suitably effective methods exist for obtaining electrical energy to run such a system. Presently, many if not most of these sensor systems are powered by solar batteries, yet certain locations experience extremely limited daylight hours seasonally, and maritime and desert areas obtain dramatically reduced electrical outputs due to the effects of salt and dust. Such difficulties make it challenging to maintain a stable sensor system.

In regard to these challenges, wave generation systems utilizing DEs to generate power through deformation alone arise as a possible way of resolving these issues (see Fig. 23.7). Experiments using wave power to generate electricity done thus far have already been able to produce 11 watts of electrical energy with small artificial

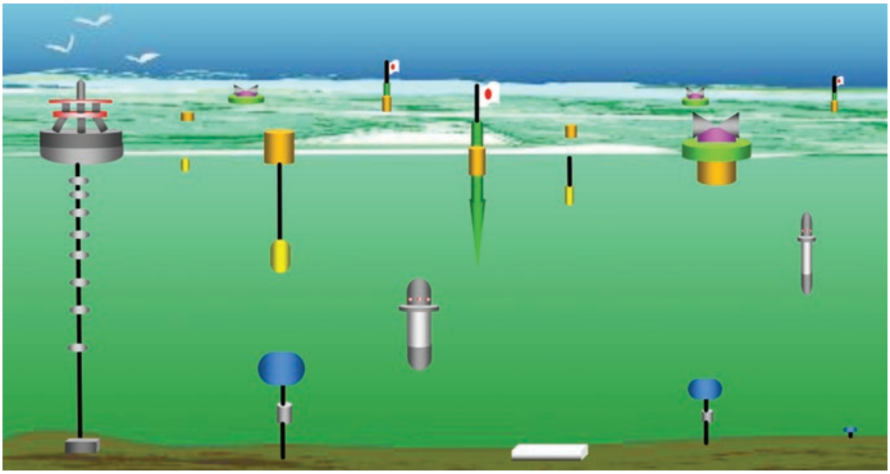


Fig. 23.7 Image of sensor systems with DE generators in oceans

muscle power generation equipment loaded onto weather observation buoys. Moreover, this system has likewise proven to be able to recharge batteries [26].

We also built a portable DE wave generator using a fairly small buoy of 90 cm in diameter [27]. At this size, it could easily be mounted on the edge of a ship, shore protection, seawall, etc. Even with waves of comparatively small height, the system was able to generate electricity.

Furthermore, we examined whether a mooring method with a sunken horizontal plate could respond to changes of sea level. We found that the mooring method could generate electrical power even in deep water.

It is known that conventional wave power generators have a tendency for a slight modification from the optimum natural period to cause a considerable decrease in generation efficiency, but the DE-based generator produces stable generated electricity over a range from short to long which, on average, represents approximately 70% of the maximum value. This is the first case in the world where this kind of electric output has been shown to be possible [28].

Recently, Moretti et al. [29] and Vertechy et al. also showed that one of the most promising applications for DEGs was in the field of wave energy harvesting [30].

Broche et al. presented wind power generation using a DEG, and they got approximately 40 mJ per cycle in a single layer device with an active elastomer volume of 0.57 cm^3.

Chiba et al. presented a simple experimental model using a flowing water tank in order to investigate the performance and feasibility of a small hydroelectric DE generation system [31, 32] (see Fig. 23.8). The mass of DE material in the power generator module was only 0.1 g. The electrical energy generated with a stroke of 10 mm was 12.54 mJ.

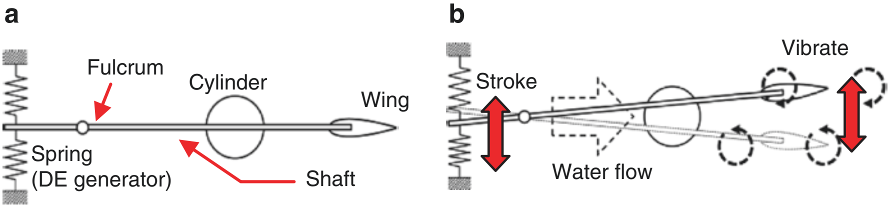


Fig. 23.8 Schematic diagrams of the system and operation principles [31, 32]

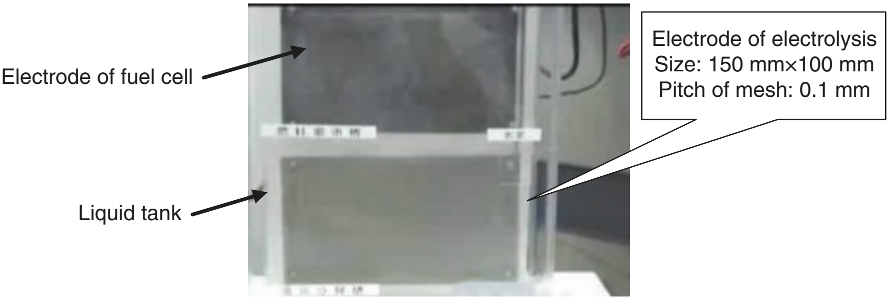


Photo 23.4 Hydrogen generation equipment by electrolysis

23.5.2 Generation of Hydrogen with DE Generators

At the time of field tests for wave power generation, we also carried out experiments on hydrogen production (see Photo 23.4). In the experiments, the generated energy was first stored in a small battery (12 V/600 mAh) [26]. This battery was connected to a hydrogen generation system via a DC-DC converter. The hydrogen generation equipment used in the experiments was a simple electrolytic cell that used nickel electrodes of a mesh of 0.1 mm (150 mm × 100 mm). Instead of seawater, a 3% aqueous solution of sodium hydroxide was used as a raw material. Applied voltages were reduced to 3 V by the DC-DC converter.

When the bias voltage was 2100 V, the amount of hydrogen generated per hour was about 14 ml in the case of the portable DE wave generator.

As mentioned above, however, we have found that approximately 11 W can be obtained by waves of just 10 cm in height, thus enabling the generation of 1.76 l of hydrogen in about 1 h (estimated for charging and discharging battery efficiencies of 80%). As with the production of electrical energy, the process could be scaled up by several orders of magnitude.

It is important to have a facility to back up the sensor network system by using the above process to turn the excess electricity into hydrogen and store the energy.

23.5.3 Water Mill Generators

In this section we discuss support for organic farming and vegetable theft prevention using sensors. In farming areas, sources of electricity can be scarce; however, small streams are often readily available (see Fig. 23.9). Electrical energy can be obtained from such small streams [6]. This system does not require a vertical drop of the water.

The flow of water rotates the water mill, and the rotational motion induces the deformation of the dielectric elastomer to generate electrical energy. Photo 23.5 shows the water mill generator using dielectric elastomers [6].

23.5.4 Solar Heat Generator Using DE

We also consider a new type of DE-based solar heat generator, which has a simple structure compared with existing solar power generators [16, 33]. Figure 23.10 shows a DE solar heat generator. When the air in front of the piston is heated by solar heat, its volume increases. The piston pushes a DE generator.

A DE cartridge has 2.8 g of acrylic elastomer and carbon black electrodes. It has a maximum power generation capability of 46.58 mJ per stroke. We used 30 cartridges. When a voltage of 3000 V is applied to a DE as a primary charge, its maximum generated energy is 1.4 J from a 5 mm stretched states to relaxed states.

Fig. 23.9 Image of water mill generator

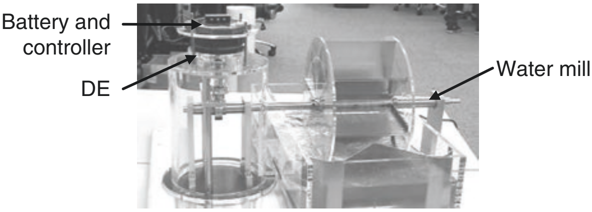


Photo 23.5 Water mill generator using DEs

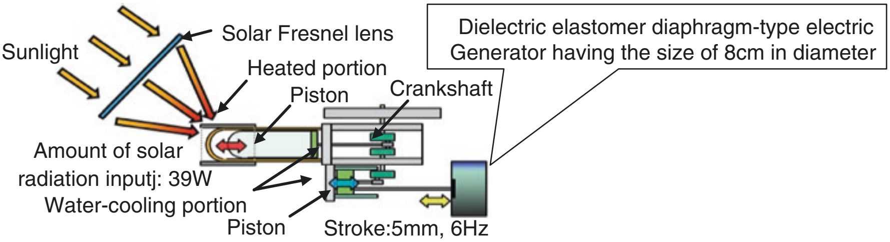


Fig. 23.10 DE solar heat generator: Fresnel lens having the effective size of 1000 mm × 1350 mm and thickness of 3 mm. The capacity of the tube was about 44 cm^3. The piston stroke was 24 mm, and the diameter of the piston was 25 mm

It turns out that the thermal loss becomes large when the temperature of a heating head becomes high. To improve power generation efficiency, it is necessary to generate at low temperature. Moreover, the emitted heat should not be emitted into the air. It should be reflected and absorbed into the heating head. It could be better to use a liquid with a lower boiling point to increase efficiency.

This system can be used anywhere solar heat may be obtained, so it has potential as a backup system for sensor network systems.

23.5.5 Sites Where Power Generation Using DEs Is Possible

Figure 23.11 shows sites where power generation using DEs is possible and conceptual rendering of the generation systems [23]. We hope that those systems may aid in responding to the threat of global warming and other large-scale environmental issues, such as the growth in world population, to maintain a better standard of living throughout the world.

23.6 Toward Mass Production

If developed further, DEs could potentially become dream materials for a worldwide life cycle engineering system with a wide range of applications in actuators, sensors, and power generation devices. However, despite the rapid advancement brought about by the growing body of research on DEs in recent years, material and application technologies remain underdeveloped. For example, elastomers with a high dielectric constant are important in the creation of functional DEs. However, when materials with high dielectric constants such as barium titanium oxide or other metal oxides are mixed with elastomers, they fail to blend well, and when they are added in quantity, the membrane becomes inflexible and unsuitable as a DE. Furthermore, when metal oxides are added to elastomers, short circuits occur. We are researching into these phenomena in collaboration with some device makers.

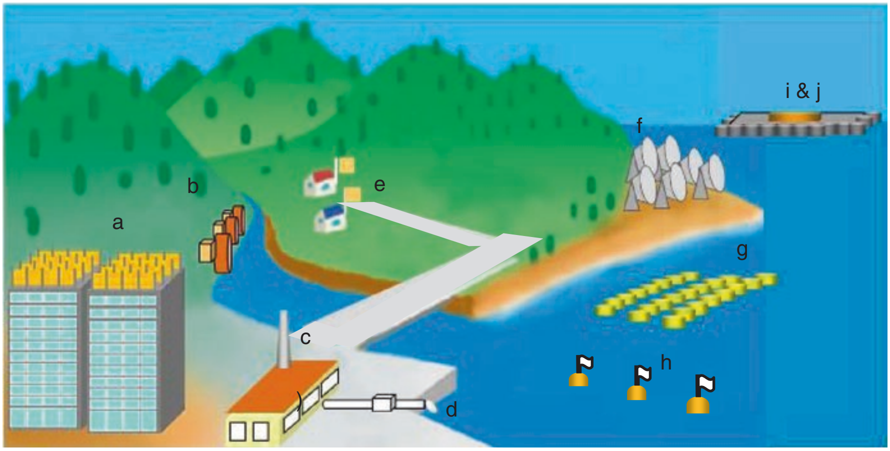


Fig. 23.11 Sites where power generation using DE is possible and conceptual rendering of the generation systems. (**a**) Wind Power Generators on tops of buildings [34–36]. (**b**) Water Mill Generators [6]. (**c**) Waste Energy Generators [36]. (**d**) Drain Generators [36]. (**e**) Wind Power Generators for Personal Houses [36]. (**f**) Solar Heat Generators [16, 33]. (**g**) Wave Generators [37–39]. (**h**) Water Flow Generators [31, 32]. (**i**) Wave Generators in Ocean [22, 37, 38]. (**j**) Hydrogen Production Plant [22, 39]

In addition, commercialization efforts and development of structures suitable for mass production must be strengthened in order to keep pace with diverse and constantly changing societal needs.

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Part IV
Green Supply Chain and Life Cycle Management

Chapter 24
Effects of Carbon Tax on Low-Carbon and Economic Supplier Selection for Asian Assembly Product

Rena Kondo, Yuki Kinoshita, Tetsuo Yamada, Norihiro Itsubo, and Masato Inoue

24.1 Introduction

To pursue lower procurement costs, materials and parts for assembly products are often produced and transported by manufacturers as a part of global supply chains including not only developed but also emerging countries. A global supply chain is carried out efficiently across multiple countries in the supply chain such as suppliers, manufacturers, distributors, retailers, and customers [1].

On the other hand, global warming is the current increase in temperature of the earth which is caused by greenhouse gas (GHG) emissions [2, 3]. The materials within the assembly products cannot avoid discharging the GHG emissions when they are produced and transported on the supply chains. Therefore, the global supply chains need to reduce the GHG emissions [4] in order to resolve a global warming problem. With regard to reducing the GHG emissions, the Paris Agreement was reached among 188 countries for progressing a sustainable low-carbon future at the 21st Conference of Parties (COP 21) in 2015. The Japanese government has compiled a plan to decrease GHG emissions by 26% from their 2013 level by 2030 [5]. As one of the methods to reduce the GHG emissions, carbon tax and emission trading system have been introduced [1]. Carbon tax is one of the environmental taxes and is paid depending on CO_2 emissions by economic activities [6]. Additionally,

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carbon prices in each country are becoming an increasingly common business tool and many firms use them in order to plan their purposes [7]. Therefore, it is expected that the carbon tax gives economic incentives to the manufacturers which have no environmental policies about the global warming [6]. Consequently, the carbon tax is given to companies and encourages us to reduce the GHG emissions efficiently.

In order to reduce the GHG emissions, it is needed to visualize the GHG emissions in the supply chains [3]. Life cycle assessment (LCA) [2] and life cycle inventory (LCI) databases [8] enable us to estimate and visualize the GHG emissions and the procurement costs for each material. The LCA is a quantitative calculation method which estimates the amount of resources gathered from the environment and materials discharged to the environment in the product life cycle [2]. Additionally, the LCI database shows a representative unit process data collected at the national or regional level covering a wide range of industries [8]. Actually, different materials of different suppliers may have different manufacturing processes. However, it is difficult and costly to collect the data for each supplier. By using the LCI database, the data collection costs can be reduced and calculated. CO_2 emissions at the material production level for the assembly supply chains for electric products and home appliances, such as copiers, mobile phones, refrigerators, air conditioners, and TVs, account for more than 90% in the forward supply chains which consisted of the part/material manufacturing, assembly manufacturing, and logistics stages [9].

The LCI database with the Asian international input-output (I/O) table has been possible to compare the environmental impact of the design of global supply chains in Asia [1]. According to the LCI database with the Asian international I/O tables, each material/part has different GHG emissions since it is depending on the country where it is manufactured [10]. This means that the GHG emission levels for each material in each country are different. One of the reasons is that an energy mix of the electric power among coals, national gases, and nuclear resources is different among the countries. Generally, materials manufactured in the developed countries have lower GHG emissions but higher procurement costs, while ones manufactured in the emerging countries have higher GHG emissions but lower procurement costs [10]. For this reason, the material/part on the global supply chain should be procured from the both developed and emerging countries to reduce the procurement costs and the GHG emissions simultaneously.

Urata et al. [1] proposed a model for an Asian global supply chain network and balanced not only the procurement/transportation cost but also the material-based CO_2 emissions. They conducted the sensitivity analysis of the emission cost with the carbon tax. The emission cost means to apply to the amount of CO_2 emissions beyond the target reduction ratio for the CO_2 emissions and added to the total costs [1]. However, only a vacuum cleaner is treated as a case study. Therefore, other products may cause different trends and features from the vacuum cleaner and change the results of supplier selection. Kuo et al. [11] and Kuo et al. [12] investigated a bi-objective optimization problem of supply chain network design in order to solve the trade-off problem for decreasing carbon footprints while ensuring cost-effectiveness. Kondo et al. [13] applied a low-carbon and economic supplier selection method to a cell phone and compared the results with two types of products. However, Kuo et al. [11], Kuo et al. [12], and Kondo et al. [13] did not select suppliers by considering the carbon tax.

This study proposes a low-carbon and economic supplier selection method by introducing the carbon tax based on Kondo et al. [13] and analyzes the carbon and economic impact of the carbon tax on the supply chain. First, a bill of materials (BOM) including the GHG emissions and the procurement costs for each part is constructed using Asian international I/O tables, and the low-carbon and economic supplier selection with the carbon tax is formulated. Second, the suppliers for each part are selected by using integer programming with ε-constraint method to achieve both the GHG emissions and the procurement/carbon cost reduction. Finally, results of the supplier selection with the carbon tax are shown, and the effect of the carbon tax is discussed.

The outline of this paper is as follows: Sect. 24.2 explains the economic and low-carbon supplier selection with carbon tax. Additionally, the formulations of the low-carbon and economic supplier selection with carbon tax are developed by using integer programming. Section 24.3 explains an example of product and supplier selection. Section 24.4 shows and discusses the results of the supplier selection with and without carbon tax. Finally, Sect. 24.5 gives conclusions and proposes future works.

24.2 Low-Carbon and Economic Supplier Selection Method with Carbon Tax

24.2.1 Overview

One of the GHG emission calculation methods is to be followed by the ISO/TS 14067. Current international specifications such as ISO/TS 14067 provide methods to calculate and collect data of GHG emissions for variety types of products [11]. It is established in order to specify principles, requirements, and guidelines for the quantification and communication of the carbon footprint for a product [14]. However, according to the carbon footprint evaluation method by Kuo et al. [12], the procurement costs cannot be calculated based on ISO/TS 14067. This study proposes an economic and low-carbon supplier selection with a carbon tax [1] based on Kondo et al. [13] as shown in Fig. 24.1. First, in step 1, a bill of materials (BOM) is constructed by identifying the types of materials and department names in the Asian international I/O tables [15]. In step 2, by considering the census of manufacture [16] and economic conditions for each country, the procurement cost for each part is estimated. After that, the GHG emissions are estimated in step 3 by using LCI databases incorporating the Asian international I/O tables. In steps 4 and 5, the economic and low-carbon supplier selection with a carbon tax is formulated by using integer programming and is optimized using a mathematical programming package with Numerical Optimizer [17].

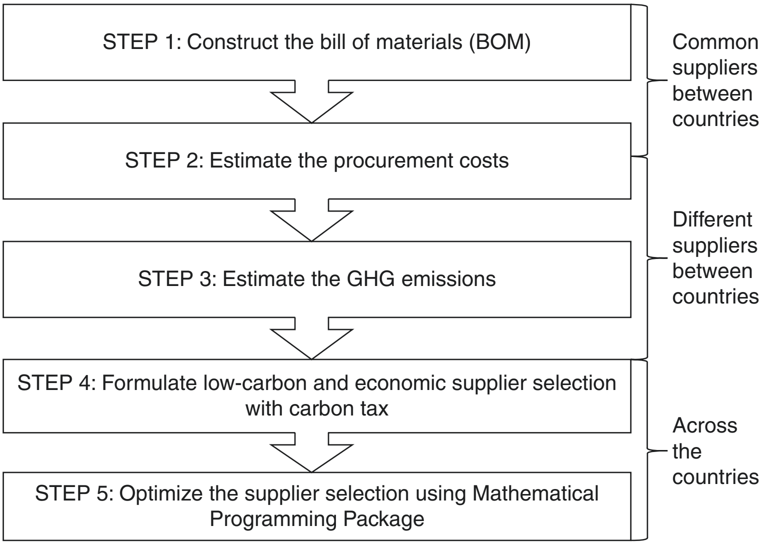

Fig. 24.1 Economic and low-carbon supplier selection of material-based GHG estimation method by using Asian international I/O tables

24.2.2 Steps 1–3: Estimation of the Procurement Costs and the GHG Emissions

Similar to Kondo et al. [13], an estimation of the procurement costs and the GHG emissions is conducted. First, the types of materials and department names in the Asian international I/O tables are identified in step 1 by constructing the bill of materials. Next, in step 2, the Japanese procurement costs for each part cannot be obtained from the 3D-CAD model; therefore, they are estimated by using the census of manufacture in Japan [16]. Additionally, since economic conditions for each country are different, the procurement cost for the materials manufactured in the other country is estimated by using a price level in each country. For example, Chinese procurement cost is assumed to be 0.517 times lower than the Japanese one [13]. In step 3, the GHG emissions are estimated by using the LCI database with Asian international I/O tables and the procurement costs for each country estimated in step 2.

24.2.3 Steps 4–5: Formulation of Economic and Low-Carbon Supplier Selection with a Carbon Tax and Optimization

In step 4, the economic and low-carbon supplier selection is formulated with a carbon tax for minimizing the procurement costs/carbon tax and the GHG emissions. This study sets two objective functions as shown in Eqs. (24.1) and (24.2). The bi-objective problem is solved by using mathematical programming package developed by Numerical Optimizer [17] in step 5. The notation and formulation are explained in detail as follows:

Equations (24.1) and (24.2) are set as the objective functions for minimizing the total procurement costs for each part considering the carbon tax and for minimizing the total GHG emissions for each part, respectively [18]. The carbon tax is calculated to multiply the amount of the GHG emissions by the tax rate. An ε-constraint method is used to solve this bi-objective optimization by transposing the objective function Eq. (24.2) to the constraint Eq. (24.3). By changing the $\varepsilon_{GHG,c}$ in Eq. (24.3), Pareto-optimal solutions are obtained. Eq. (24.4) ensures that all necessary parts must be procured from the suppliers. The constraint set in Eq. (24.5) ensures that the transported part f_{lj} is equal to or above the minimum order quantity $Q_{min,lj}$ from supplier l. Eq. (24.6) means that each part j is provided from only assigned supplier l.

$$\mathrm{TPC} = \sum_{j \in J}\sum_{l \in L}\left(PC_{lj} + e_{lj}\mathrm{CTAX}\right) f_{lj} \rightarrow \min \tag{24.1}$$

$$\mathrm{E} = \sum_{j \in J}\sum_{l \in L} e_{lj} f_{lj} \rightarrow \min \tag{24.2}$$

s.t.

$$\mathrm{E} \le \varepsilon_{GHG,c} E_{max} \tag{24.3}$$

$$\sum_{l \in L} f_{lj} = n_j N_{product} \quad \forall j \in J \tag{24.4}$$

$$f_{lj} \ge Q_{min,lj} S_{lj} \quad \forall l \in L, \forall j \in J \tag{24.5}$$

$$f_{lj} \le \mathrm{M} S_{lj} \quad \forall l \in L, \forall j \in J \tag{24.6}$$

J: Set of parts, $J = \{1,2,\ldots,j,\ldots,|J|\}$.
L: Set of suppliers, $L = \{1,2,\ldots,l,\ldots,|L|\}$.
PC_{lj}: Procurement cost of part j at supplier l.
e_{lj}: GHG emissions of part j at supplier l.
E_{max}: Total GHG emissions of the initial configuration.
$\varepsilon_{GHG,c}$: Constraint of total GHG emissions.
f_{lj}: Number of part j transported at supplier l.
n_j: Number of part j needed for a product.
$N_{product}$: Number of product demand.
$Q_{min,\,lj}$: Minimum order quantity from supplier l for part j.
M: Very large number (Big M).
S_{lj}: 1, if supplier l supplies part j.
0, otherwise.
$CTAX$: Unit cost of carbon tax per ton.

24.3 Problems

24.3.1 *Product Example*

In this study, GHG estimation method [18] is adopted to a cell phone [15] as well as Kondo et al. [13]. The system boundary is defined as a boundary from nature including the whole processes at LCA [2, 3] and is set for raw material production and logistics in this study. The GHG emissions including raw material production and logistics are estimated by using the LCI database with Asian international input-output (I/O) tables as a background data. Similar to Kondo et al. [13], this study uses the 3D-CAD model of the cell phone. Its part and material name, the number of parts, and weight for each part are obtained from the 3D-CAD model [19, 20]. Table 24.1 shows the BOM of each part for the cell phone [15]. From Table 24.1, it is found that the cell phone consisted of 12 parts and 6 material types, and the most used material is polycarbonate which is used in 5 parts of the cell phone. Furthermore, the part #4 board is the heaviest part and accounts for 42% of the total weight.

In order to construct the BOM with the procurement cost and the GHG emission information, the data such as weight and necessary number of parts for a product is also shown in Table 24.1. Moreover, the material unit prices based on the census of manufacture [16] are given. The procurement cost and the GHG emission for each part are calculated in steps 2 and 3 as shown in Fig. 24.1, respectively.

However, unit material prices for battery and circuit board cannot be calculated since the amount of production for them is not written on the census of manufacture. To deal with this issue, prices of battery and circuit board are assumed as 0.1 [Japanese yen], respectively. Additionally, the part #11 LCD made of glass, the procurement costs and the GHG emissions are assumed as 0 [yen] and 0 [g-CO_2eq], respectively, since the weights for the glass account for only 0.49%. Moreover, this study assumes that the type of the cell phone is an older type and is not a smartphone in the current market. It is considered that the weight of LCD part in the cell phone might be lighter than that in a general smartphone.

24.3.2 *Scenarios of Supplier Selection with Carbon Tax*

A carbon tax is one of the environmental taxes and is paid depending on CO_2 emissions by economic activities [6]. The recent carbon pricing in each country is as follows:

1. In Japan, the carbon tax is 289 [yen] per ton [21].
2. In Australia, the carbon is priced at $23 per ton in 2012 and then rising to $24.15 in 2013 and $25.40 in 2014 [7].
3. In the US corporate prices, carbon tax ranges from $6–7 per ton of CO_2 equivalent at Microsoft to $60 per ton of CO_2 equivalent at ExxonMobil [7].

Table 24.1 BOM of each part for the cell phone [15]

Part number	Part name	Material number	Material name	Number [piece]	Weight [g]	Unit price of each material [yen/g]	Procurement cost [yen]		GHG emission [g-CO_2eq]	
							Japan	China	Japan	China
1	Battery cover	1	Polycarbonate	1	1.00	0.29	0.29	0.15	2.24	10.69
2	Battery	2	Battery	1	58.10	0.10	5.81	3.00	19.33	137.92
3	Back case	1	Polycarbonate	1	1.00	0.29	0.29	0.15	2.24	10.69
4	Board	3	Circuit board	1	85.40	0.10	8.54	4.42	34.15	126.87
5	Microphone	4	SUS	1	0.50	0.22	0.11	0.06	0.82	5.25
6	Camera	5	Zinc alloy	1	5.30	0.14	0.77	0.40	3.57	27.99
7	Main button	1	Polycarbonate	1	1.00	0.29	0.29	0.15	2.24	10.69
8	Number button	1	Polycarbonate	1	1.00	0.29	0.29	0.15	2.24	10.69
9	Junction	4	SUS	1	47.50	0.22	10.67	5.52	77.64	498.69
10	Front case	1	Polycarbonate	1	1.00	0.29	0.29	0.15	2.24	10.69
11	LCD	6	Glass	1	1.00	0.00	0.00	0.00	0.00	0.00
12	Speaker	4	SUS	1	0.60	0.22	0.13	0.07	0.98	6.30
Average				1	16.95	0.21	2.29	1.19	12.31	71.37
Total				12	203.40	–	27.48	14.22	147.69	856.47

With respect to the low-carbon and economic supplier selection, there are two cases of cost minimization: with and without carbon tax. The cost minimization with the carbon tax proposed in this study is to minimize the sum of the procurement costs and the carbon tax. On the other hand, one without the carbon tax [18] means to minimize the procurement costs without the carbon tax under the reduction ratios for the GHG emissions from 0% to 50%.

The assumptions of the example problem for the supplier selection are as follows:

1. It is assumed that each part can be procured from two suppliers. One supplier is located in Japan as a developed country, while the other supplier is located in China as an emerging country. The reason why these two countries are chosen is that China is Japan's largest import country and second largest export country [22].
2. Each country has one supplier for each part.
3. The number of product demand is not a decision variable but fixed parameter in this study. This study also assumes that the number of product demand is 1000 products. Therefore, each part is procured to add up each product demand.
4. Minimum order quantity for each supplier is 1 in this study.
5. The part #11 LCD used with glass is procured from Japan because the percentages of weights for the glass are too small such as 0.49%.

24.4 Results

24.4.1 With vs Without Carbon Tax

In order to examine the effect of the costs for the GHG emissions reduction, this section compares the two cases with or without carbon tax.

Figure 24.2 shows the behaviors of the total procurement costs for the total GHG emissions. In the case without the carbon tax, the total procurement costs are monotonically increased, but the GHG emissions are decreased as the target reduction ratio for the GHG emissions is increased.

On the other hand, in the case with the carbon tax, the GHG emissions are slightly decreased by 1% only as the carbon tax is increased from 0 to 11,560 [yen/t]. However, when the carbon tax is increased from 11,560 [yen/t] to 14,450 [yen/t], the GHG emissions are decreased by 50%, but the procurement costs are slightly increased by 6% only as the carbon tax is increased. When the carbon tax is increased from 17,340 [yen/t] to 26,010 [yen/t], the GHG emissions are decreased by 33%, and the procurement costs are increased by 11%.

Therefore, when the carbon tax is lower until 11,560 [yen/t], it is considered that the case without the carbon tax is more effective than the case with the carbon tax. On the other hand, when the carbon tax is higher more than 11,560 [yen/t], the case with the carbon tax is superior to the case without the carbon tax.

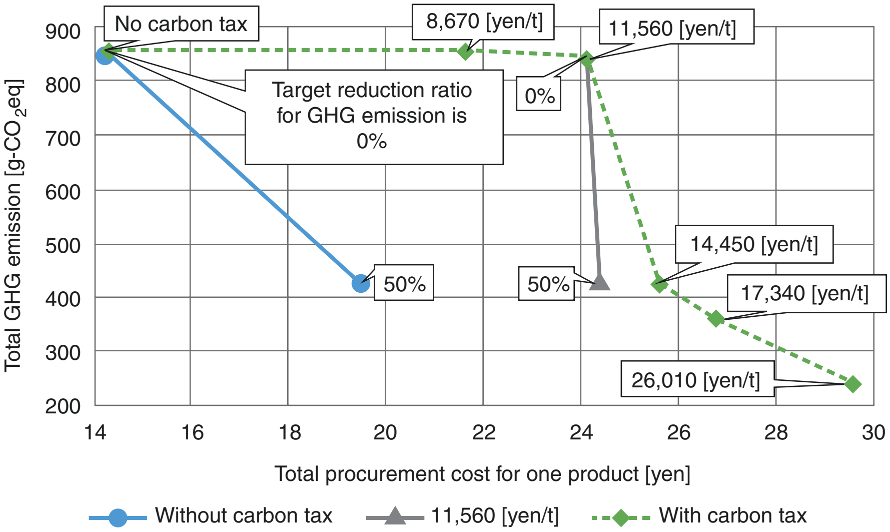

Fig. 24.2 Behaviors of the total procurement costs for the total GHG emissions: without and with carbon tax

24.4.2 Results of Supplier Selection

In order to examine how the results of the supplier selection are changed between the cases with and without carbon tax, this section compares them with the carbon tax for 11,560 [yen/t] and without carbon tax.

From Fig. 24.2, when the carbon tax is 11,560 [yen/t], the behaviors of the total procurement costs for the GHG emissions become different between the case with and without the carbon tax. In the case without the carbon tax, the total procurement costs are increased by 37% in target reduction ratio for the GHG emissions from 0% to 50%. On the other hand, when the carbon tax is 11,560 [yen/t], the total procurement costs are increased by 1% only in target reduction ratio for the GHG emissions from 0% to 50%.

Tables 24.2 and 24.3 show the results of the supplier selection for each part in the case with and without the carbon tax for 11,560 [yen/t], respectively.

From Tables 24.2 and 24.3, the results of the supplier selection in the case with the carbon tax for 11,560 [yen/t] are similar to the one without the carbon tax in terms of the number of parts procured from each supplier. Additionally, the number of parts procured from a Japanese supplier for the part #9 junction in Table 24.3 is the same as the case without the carbon tax in Table 24.2 at any target reduction ratio for the GHG emissions. Since #9 junction has highest procurement cost by 39% in the total procurement costs and GHG emissions by 53% and 58% in the Japanese total GHG emissions and Chinese ones, respectively, the same supplier selection for the #9 junction in both of the cases is obtained in spite of the different behaviors of the procurement costs for the GHG emissions. Furthermore, the number of parts procured from the Japanese suppliers for the part #5 microphone, #6

Table 24.2 Results of supplier selections for each part in the case without the carbon tax (J, Japan; C, China)

	Procurement cost [yen]		GHG emission [g-CO_2eq]		Target reduction ratio for GHG emission (%)									
					0%		6%		26%		30%		50%	
Part number	J	C	J	C	J	C	J	C	J	C	J	C	J	C
1	0.29	0.15	2.24	10.69	0	1000	0	1000	0	1000	0	1000	0	1000
2	5.81	3.00	19.33	137.92	0	1000	0	1000	0	1000	0	1000	0	1000
3	0.29	0.15	2.24	10.69	0	1000	0	1000	0	1000	0	1000	0	1000
4	8.54	4.42	34.15	126.87	0	1000	0	1000	0	1000	0	1000	0	1000
5	0.11	0.06	0.82	5.25	0	1000	991	9	978	22	998	2	995	5
6	0.77	0.40	3.57	27.99	0	1000	0	1000	0	1000	2	998	0	1000
7	0.29	0.15	2.24	10.69	0	1000	0	1000	0	1000	0	1000	0	1000
8	0.29	0.15	2.24	10.69	0	1000	0	1000	0	1000	0	1000	0	1000
9	10.67	5.52	77.64	498.69	0	1000	99	901	506	494	587	413	994	6
10	0.29	0.15	2.24	10.69	0	1000	0	1000	0	1000	0	1000	0	1000
11	0.00	0.00	0.00	0.00	1000	0	1000	0	1000	0	1000	0	1000	0
12	0.13	0.07	0.98	6.30	0	1000	999	1	996	4	999	1	997	3
Total procurement cost [yen]					14220.00		14839.34		16934.56		17353.63		19448.67	
Total GHG emission [g-CO_2eq]					856470.00		805081.24		633787.44		599528.99		428234.41	
Total procurement cost [yen] per one product					14.22		14.84		16.93		17.35		19.45	
Total GHG emission [g-CO_2eq] per one product					856.47		805.08		633.79		599.53		428.23	

Table 24.3 Results of supplier selections for each part in the case with the carbon tax for 11,560 [yen / t] (J, Japan; C, China)

	Procurement cost [yen]		GHG emission [g-CO_2eq]		Target reduction ratio for GHG emission (%)									
					0%		6%		26%		30%		50%	
Part number	J	C	J	C	J	C	J	C	J	C	J	C	J	C
1	0.29	0.15	2.24	10.69	0	1000	0	1000	0	1000	0	1000	0	1000
2	5.81	3.00	19.33	137.92	0	1000	0	1000	0	1000	0	1000	0	1000
3	0.29	0.15	2.24	10.69	0	1000	0	1000	0	1000	2	998	0	1000
4	8.54	4.42	34.15	126.87	0	1000	0	1000	0	1000	0	1000	0	1000
5	0.11	0.06	0.82	5.25	1000	0	1000	0	1000	0	1000	0	1000	0
6	0.77	0.40	3.57	27.99	0	1000	0	1000	0	1000	1	999	0	1000
7	0.29	0.15	2.24	10.69	0	1000	0	1000	0	1000	0	1000	0	1000
8	0.29	0.15	2.24	10.69	0	1000	0	1000	0	1000	0	1000	0	1000
9	10.67	5.52	77.64	498.69	0	1000	99	901	506	494	587	413	994	6
10	0.29	0.15	2.24	10.69	0	1000	0	1000	0	1000	0	1000	0	1000
11	0.00	0.00	0.00	0.00	1000	0	1000	0	1000	0	1000	0	1000	0
12	0.13	0.07	0.98	6.30	1000	0	1000	0	1000	0	1000	0	1000	0
Total procurement cost [yen]					24118.08		24146.07		24261.11		24284.18		24399.05	
Total GHG emission [g-CO_2eq]					846720.00		805036.05		633668.70		599522.33		428196.30	
Total procurement cost [yen] per one product					24.12		24.15		24.26		24.28		24.40	
Total GHG emission [g-CO_2eq] per one product					846.72		805.04		633.67		599.52		428.20	

camera, and #12 speaker is changed by comparing to one without carbon tax. It is considered that these parts are procured by adjusting the total GHG emissions for the target reduction ratio.

Therefore, the carbon tax with 11,560 [yen/t] brings the reduction of the total GHG emissions effectively by 50% with small increments of the total procurement costs by 1%, and less changes for the supplier selection.

24.5 Summary and Future Works

This study proposed a low-carbon and economic supplier selection method by introducing the carbon tax based on Kondo et al. [13] and analyzed the carbon and economic impact of the carbon tax on the supply chain. First, the BOM including the GHG emissions and the procurement costs for each part was constructed using Asian international I/O tables, and the low-carbon and economic supplier selection with the carbon tax was formulated. Second, the suppliers for each part were selected by using integer programming with ε-constraint method to achieve both the GHG emissions and the procurement/carbon cost reduction. Finally, the results of the supplier selection with the carbon tax were shown, and the effects of the carbon tax and pricing were discussed. The main findings are as follows:

1. When the carbon tax is lower than 11,560 [yen/t], it is considered that the case without the carbon tax is more effective than one with the carbon tax. On the other hand, when the carbon tax is higher than 11,560 [yen/t], the case with the carbon tax is superior to one without the carbon tax for reducing the GHG emissions in the experiment.
2. The carbon tax with 11,560 [yen/t] brings the reduction of the total GHG emissions effectively by 50% with small increments of the total procurement costs by 1% and less changes for the supplier selection.

Further studies should adopt to other types of products by the 3D-CAD models and other countries in the LCI databases with Asian I/O tables. Another study should select suppliers by considering the lead time and different number of product demand.

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Chapter 25
A Study on Specification of Information System for Product Life Cycle Management in IoT Era

Keijiro Masui and Mitsutaka Matsumoto

25.1 Introduction

To recycle scarce resources, especially rare metals, more efficiently, it is crucial to establish a mechanism in which manufacturers and recyclers share information, including the appropriate post-use treatment of products. In recent years, information sharing through the Internet of Things (IoT) has become easier due to lower-priced sensors and the increasingly sophisticated network communication technologies [1]. This ease of information sharing should be utilized not only in manufacturing and product sales but also in managing products throughout their life cycle, which includes maintenance and disposal [2].

This study extracts requirements for product life cycle management information systems. That is, information that should be provided by manufacturers to recyclers with a focus on product specifications and other information useful for product life cycle management are identified. To more efficiently share information, a two-way distribution is essential: information distribution from recyclers (“venous” sector) to manufacturers (“arterial” sector) and vice versa. The former helps manufacturers realize the concept of Design for Resource (DfR), whereas the latter helps recyclers improve the efficiency of their recycling process.

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25.2 Requirements for Product Life Cycle Management Information Systems

25.2.1 Relation Between Manufacturers and Recyclers in Product Recycling

A sustainable material life cycle requires information sharing between the actors in the product life cycle [3–5], specifically between manufacturers and recyclers. In order to increase recoverability and resource efficiency, it is important that manufacturers take into consideration the recovery phase at the design stage [6]. The information on product design and DfR should be shared with recyclers to increase the products' recoverability. In addition, because manufacturers are not always involved in treatment operations [7] and thus lack in knowledge on the recovery strategies and products' end-of-life situations, information feedback from recyclers to manufacturers is also needed to improve the effectiveness of DfR.

Product recycle information can be roughly classified into two groups: information about product structure, materials (resources), and performance (hereinafter referred to as "product information") and information about how to handle a product during and after use, including disassembly, treatment, and recycling of the product (hereinafter referred to as "recycle information"). Typically, manufacturers provide the former, and the recyclers provide the latter. In a recycle scheme where manufacturers assume greater responsibility, and consequently play a major role in product recycling, manufacturers hold more information. Regardless of the recycling scheme, it is necessary that both manufacturers and recyclers receive certain merits, or at a minimum do not receive demerits, when sharing information.

This study identifies the merits and demerits that manufacturers and recyclers receive from the product or recycle information items. It is assumed that the product and recycle information is composed of the following elements described in Sects. 25.2.2 and 25.2.3. The aim of this study is to identify the information item which is effective as product information and recycle information.

25.2.2 Product Information

- Materials, resources, and hazard substances used in the product (type, content, and location).
- Product structure.
- Product and part performances.
- Product identifier necessary to link the above information with the product.

25.2.3 Recycle Information

- Costs required for the appropriate treatment and recycling, product's structure to reduce treatment and/or recycle costs, and the amount of resources needed for cost-effective material recovery.
- End-of-life (EoL) conditions of a product and consumer's usage of the product.
- Energy consumption and environmental loads associated with product recycling.
- Outcomes of product recycling and/or treatment of wastes containing hazardous substances.

25.3 Validation of the Usefulness of Product Life Cycle Management Information by Interview Survey

25.3.1 Interview Subjects

To validate the usefulness of current information about product life cycle management, we conducted an interview survey. The questions inquired about the current situation regarding the utilization of information obtained from discarded products possessed by recyclers (venous sector) and the possibilities of future utilization of such information. We selected ten interviewee companies from the four groups based on their business types (Table 25.1). The Home Appliance Recycling Law in Japan obliges the manufacturers of the subject products to be responsible for the end-of-life treatment of the products. The information sharing between manufacturers and recyclers is expected to be advanced, and thus we included them in the interviewee companies. On the other hand, the information sharing in the other product categories is presumably under development. The companies in such product areas were also targeted to contrast the situations in the home appliance product areas. The interview lasted 1–2 h for each company.

Table 25.1 Interviewed companies

Classification	Number of companies
Manufacturers of products covered by the Home Appliance Recycling Law	2
Recyclers of products covered by the Home Appliance Recycling Law	2
Manufacturers of electric and electronic equipment *not* covered by the Home Appliance Recycling Law	3
Recyclers of electric and electronic equipment *not* covered by the Home Appliance Recycling Law	3

25.3.2 Survey Items

There were three main survey items as follows:

1. Current situation and challenges in information sharing between manufacturers and recyclers regarding product recycle.
2. Status of development of product design guidelines necessary to promote recycling of rare metals and the kinds of information shared between manufacturers and recyclers.
3. Challenges to be tackled to establish an information sharing system.

In each interview, the survey items were deployed into more concrete questions based on the subject company's affiliation (manufacturer or recycler). The questionnaire which was sent to manufacturers and recyclers before interviews includes the more concrete question topics as follows:

- Current situation of product recycling (implementation, organizational structure for recycling, development, and utilization of product design guidelines for recycling).
- Current status of information sharing about cost for proper treatment and recycling of products, product structure designed to reduce costs, and the quantity that allows types of cost-effective recovery of resources.
- Current status of information sharing about the end-of-life (EoL) product and consumer's usage of the product.
- Current status of information sharing about energy consumption and environmental loads associated with product recycling.
- Current status of information sharing about the outcomes of product recycling and/or treatment of wastes containing hazardous substances.
- Measures to share information and obstacles that hinder information sharing.
- And other topics.

25.4 Study Results and Considerations

25.4.1 Current Situation and Existing Challenges in Information Sharing Between Manufacturers and Recyclers Regarding Product Recycling

Prior to organizing and analyzing the interview results, this study classified electrical appliances into three groups. Each type of electrical appliance (excluding automobiles but including EEE) has its own characteristic recycle scheme, resulting in differences in the contents and measures of information sharing.

25.4.1.1 Home Appliances

- Manufacturers of home appliances are motivated by incentives to reduce the costs of waste treatment and recycling. Collection routes for used home appliances are well established, and manufacturers bear responsibility to meet recycling targets.
- For products where manufacturers are mainly obligated for treatment and state governments or consumers (e.g., home appliances) exert pressure to reduce costs, providing recyclers with identifier information (e.g., product number) can contribute to treatment cost reduction by increasing treatment speed and efficiency.
- Our interviews found that many recyclers have a common disassembly manual.
- In another example, a manufacturer provided recyclers with data linking a product number with used refrigerant and heat insulating materials to increase the efficiency of refrigerator disposal processes.
- As an example, the Panasonic Eco Technology Center (PETEC) has developed a database of manufacturers' refrigerators, including type of refrigerants and other materials, to increase the efficiency of refrigerant and insulating materials treatment. The Center identifies the model number of each discarded refrigerator. Then the type of used refrigerant is determined using the database. Next a label sticker is attached to the product. The label color represents the type of refrigerant, and the product is sent to the next process, increasing the efficiency of the treatment processes. In particular, this approach becomes useful when recyclers want to save work for pre-treatment prior to disassembly or the crushing process. Furthermore, similar approaches can be applied for the removal or treatment of refrigerant used in vending machines (e.g., cyclopentane, which is flammable).
- Another challenge for recycling home appliances is sharing of information about parts that may help to improve the treatment efficiency (e.g., energy efficiency or the introduction of automation technologies) as well as information about the proper and safe disposal of mercury, fluorocarbons, waste requiring special control, and various additives contained in resins.

25.4.1.2 Small Home Appliances

- In the small home appliance industry, information sharing between manufacturers and recyclers is not advanced because the obligation of small home appliance manufacturers is currently limited to the reduction of recycling costs through product design and utilization of recycled materials. There are two other reasons limiting information sharing: stable collection routes have yet to be established for small home appliances, and the prices of rare metals are low.

- When recyclers buy discarded small home appliances from local governments, they are typically not segregated. Manufacturers do not share much information with recyclers because recyclers determine the resource value of the collected products based on their accumulated information and know-how. Information shared between manufacturers and recyclers about small home appliances includes the metal content of positive-electrode materials of small Li-ion batteries.
- To promote sharing information (e.g., information about the resource value of collected products) between manufacturers and recyclers, changes in the recycle scheme based on Japanese "Act on Promotion of Recycling of Small Waste Electrical and Electronic Equipment" [8] may be needed. Such changes may include imposing a target for the recycle rate instead of a target for the amount of collected products.
- To disassemble and treat small home appliances, office automation equipment, or point-of-sale (POS) cash registers, recyclers note that manufacturers must share information about the location of Li-ion batteries, which are ignitable, in products.

25.4.1.3 Other Apparatuses (Copiers, Information Processors, Communication Devices, and Vending Machines)

- To recycle copiers, product-related information, including the status of usage, is shared between the manufacturers and recyclers. Recyclers are operated directly by the manufacturer or by subsidiaries of the manufacturer as a part of efforts to reuse, remanufacture, and recycle. For example, a recycle factory of Ricoh, which is located in Gotemba City, Shizuoka, Japan, utilizes information, including product usage history, to determine how to treat each product when the products are returned to the factory.
- Information such as product design that allows easier recycling and disassembly is shared between manufacturers and recyclers of the industries of copiers, information processors, communication devices, and vending machines.
- Both manufacturers and recyclers hold information about the precious metal content (e.g., gold, silver, and copper) of each product and record of recovered amounts of such metals. Rare metal recycling is similar to the situations for home appliances and small home appliances. That is, there are no significant financial incentives, and information sharing is not advanced.
- For used products collected after their lease contracts are expired, obtaining product/recycle information can be difficult due to language and/or security issues.

25.4.2 Product Design Guidelines and the Information to Be Shared Between Manufacturers and Recyclers with the Aim of Enhancing Rare Metal Recycling

25.4.2.1 Sharing Information to Reduce Costs of Waste Treatment and Recycling

- To enhance the recyclability of rare metals, efforts to provide information about the presence of parts containing rare metals have been continued based on recyclers' requests. However, our interviews did not reveal any other efforts to facilitate rare metal recycling. This might be due to the current low prices of rare metals, which limit financial incentives.
- When considering cases where information is provided from manufacturers to recyclers, products in which manufacturers pay treatment costs as a part of their enhanced producer responsibility (EPR) may more easily reduce the costs of waste treatment and recycling. However, reducing such costs through the recovery of rare metals under the existing scheme is difficult for small home appliances. It should be noted that when the recycling costs are paid by consumers and such recycling fees are classified based on the recyclability of the products, information should be provided from the perspective of product differentiation.

25.4.2.2 Information Provision from Manufacturers to Recyclers

- When advanced technologies are introduced to waste sorting (e.g., single-stream collection, image recognition, advanced sensing, IoT, artificial intelligence, or robotics), the need for sharing of product/recycle information using the product model number as an identifier should grow because advanced technologies require information about product composition, hazardous substances contained in fire-retarding materials, or batteries.
- PETEC is considering a labeling scheme for the neodymium magnet cutting process. In this potential scheme, a label, which contains the product structure and materials, will be attached to every product to be treated at the Center. Furthermore, if the neodymium magnet cutting and/or disassembling processes are automated, information sharing about the product structure and materials is beneficial not only from the perspective of determining specific treatments for each product but also from the perspective of efficient operation of treatment machines.

25.4.2.3 Information Provisions from Recyclers to Manufacturers

- Home appliance recyclers have proposed product design based on their recycling experiences to manufacturers. However, our interviews did not find any manufacturers' demands for additional information from recyclers, although such demands may be useful when developing next-generation products (e.g., products that can be collected by recyclers or can indicate the degradation status of parts). Similarly, recyclers barely recognize that they possess information that is potentially useful for manufacturers.
- Information about recycling-related environmental loads (e.g., the amount of CO_2 emitted from the recycling processes) is uniquely held by recyclers. If manufacturers intend to design products that meet environmental regulations or are particularly environment-friendly, manufacturers may require such information from recyclers.

25.4.2.4 Information Sharing with Refining Companies

- To recycle small home appliance, recyclers typically buy used appliances that have been collected by municipal governments through tenders. The bid prices are determined based on the recyclers' estimated recourse value of the collected appliances using past experiences.
- Given the current situation, if information about the grade as metallic resource of and/or substances contained in the appliances is shared, bid prices may be determined more efficiently. In theory, if a scheme is established where each product's model number is used to identify resources to be recovered from the product, refining companies can know when purchasing goods collected by recyclers. However, from the scope of this study, the feasibility of this scheme seems low because numerous challenges remain to realize such a scheme such as the unstable quality of collected goods and difficulties in coordination among stakeholders.

25.5 Conclusion

This study extracted the requirements for product life cycle management information systems by establishing the assumptions for current status of retainment of information necessary for product life cycle management. These requirements were used to design the questions for the interview survey. Then both manufacturers and recyclers were interviewed.

Table 25.2 shows information items related to the product life cycle, which is confirmed to be useful when provided by manufacturers ("arterial" sector) to recyclers ("venous" sector). Recyclers of home appliances indicated that information about the following items would be useful from the manufacturer: weight and size

Table 25.2 Candidate product life cycle information items

Time product is manufactured	Weight and size of the product
Type, quantity, and location of major components	Type, quantity, and location of plastic materials
Type, quantity, and location of hazardous substances	Type and quantity of chemical substances (e.g., refrigerant)
Type, quantity, and location of rare metals	Product disassembly instructions

of products, presence of neodymium magnets in air conditioners, types of insulating material used in refrigerators, types of refrigerant used in refrigerators, and air conditioners. Recyclers of small home appliances indicated that the following information would be useful: the presence of secondary batteries, how to remove the batteries (if any, for the safety reason), and the presence of valuable rare metals. Such product information should improve the efficiency of recycling processes and recyclability of products (horizontal recycling). For some home appliances, manufacturers already provide some of this information to recyclers, but the quality of information could be improved. In particular, for the type, quantity, and location of constituent materials containing rare metals, manufacturers may be required to collect additional information upstream of the supply chain (part and/or constituent material manufacturers). The chemSHERPA [9, 10], which aims to help industries calculate chemical substances contained in their products, has been developed to ensure the conformity to the RoHS directive issued by EU. It can help manufacturers obtain such additional information. Furthermore, it is important to discuss potential information sharing systems with future sophisticated recycling technologies, including automated processes as well as information sharing given the prevailing recycle processes.

Our interview survey identified the efficacy of information shared from the venous sector to the arterial sector. In our interview, a copier manufacturer answered that it utilized data of product conditions during and after use to determine the appropriate treatment processes such as whether to reuse or remanufacture. Other appliances' manufacturers and recyclers answered that the recyclers do not provide any feedback to the manufacturer about discarded products, and only customers give feedback about products to the manufacturers (e.g., failures and/or product lifetime). Similar to the situations reported by Lindkvist et al. [5] based on the case studies in Sweden, this study found the situation that manufacturers have limited access to information from the recyclers. On the other hand, there was an opinion that analyzing discarded products is an effective method to identify failures that originate in the manufacturing processes but not in the product design process.

Based on the above discussion, information about the relationship between product design and product lifetime currently seems to be used only in the copier industry, which reuses and remanufactures products. The needs for sharing such information may be necessary in the future as failure detection, product data management, and IoT technologies advance and recycling processes are automated.

25.6 Future Challenges

This study identifies two future challenges to realize information: closing the information gap between manufacturers and recyclers and utilizing platforms to enhance information sharing.

25.6.1 Closing the Gaps Between Information Held by Manufacturers and Recyclers

- When a manufacturer recycles its products by itself, there are not significant gaps between the manufacturer and recycler. However, when recycling is conducted by a different company, gaps may exist between the accuracy of information that manufacturer and recycler have.
- Examples include a gap between the quantity of rare metals in the product (information held by manufacturers) and the quantity of such metals that can be cost-effectively recovered in actual recycle processes (data held by recyclers) as well as a gap between the quantity of rare metals in the product (information held by manufacturers) and the quantity of such metals that can be theoretically recovered using sophisticated segregation machines (data held by researchers).
- When different agencies share information, platforms or mechanisms to coordinate or bridge information may help with efficient information sharing. The mechanism or platform's function should be similar to the function of Ecology Net, a management firm for Group A manufacturers under the Japanese Home Appliance Recycling Law.
- A demonstration project that involves diverse stakeholders may effectively establish consensus among all stakeholders. Initial demonstration projects should focus on copier or home appliance recycling because the information gap between manufacturers and recyclers is small in these areas.
- If the scope of a demonstration project includes establishing standards for recycle-related information sharing, recycling of small home appliances is a suitable topic because guidelines may be created to deal with diverse products.

25.6.2 Utilization of Platforms for Sharing Information About Product Design and Chemical Substances Contained in Products

- When manufacturers recycle their product by themselves, as seen in the case of copier recycling, the manufacturer also holds data about product use. Hence, information is shared and utilized indirectly in the recycling processes as the manufacturer selects which products to reuse.

- There is no demerit in sharing information about product design (e.g., CAD data). However, when a product has a number of parts manufactured or supplied by external companies, difficulties arise in collecting necessary information. In some cases, necessary data cannot be provided without laws or regulations mandating a data provision.
- Existing efforts in the chemical industry may be useful. In the chemical industry, information about chemical substances contained in products is communicated throughout the supply chain. Regulations governing chemical substances include the EU's RoHS directive restrict the use of specified hazardous substances by component as mandated in EEE. Under such regulations, the chemical industry has implemented a scheme where chemical substance-related information is communicated along the flow of "product–parts–components–chemical substances contained in components" throughout the supply chain. This data is eventually compiled by the manufacturer, which assesses compliance with relevant regulations.
- In Fall 2015, chemSHERPA [9, 10], which was developed to further improve the efficiency of communications regarding chemical substances contained in products, was released. Today, compliance with regulations of chemical substances contained in products is crucial. Although chemSHERPA was developed with the sole purpose of ensuring compliance with chemical substance regulations, this concept may be applied to recycling-related information sharing. The functions necessary to share information necessary to recycle rare materials are already established. Because establishing a new stream to distribute information throughout the supply chain would be burdensome on all entities, utilization of an existing mechanism like chemSHERPA will be easier to implement.
- The addition of a new function to CAD (e.g., to display position data) may reduce the workload associated with information distribution.

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Chapter 26
Environmental Impacts of Japanese Micro Van Electrification Based on Real-World Use Cases

Keita Sasaki and Tetsushi Mimuro

26.1 Introduction

In recent years, in order to prevent global warming, further reductions in greenhouse gas emissions are required in all sectors in the world. The pie chart of Japan's CO_2 emissions by sectors is shown in Fig. 26.1. The transport sector accounts for 17.4%, and 35.8% of the sector is from commercial vehicles. Freight transportation is essential not only for industries but also for our daily lives, and its demand will increase more and more due to the spread of online shopping in the future. Among 15 million commercial vehicles registered in Japan, 59% are "Kei cars" (Japanese mini cars).

Kei cars are restricted in body sizes, engine displacement (less than 660 cc), and seating (maximum seating capacity is four) and so on according to its regulations. Also, Kei cars have various body types such as vans and trucks in addition to sedans and hatchbacks. Kei commercial cars are widely used by commercial users because of cheaper taxes, lower prices, and running costs. In this study, we focus on Kei vans (micro vans) which are often used for parcel delivery services. They have 2864 thousand registrations in Japan.

Generally speaking on commercial vehicles, heavy-duty trucks are used for inter-city large-scale transport, and light-duty trucks are for inner-city delivery. So, the common operation style of micro vans would include frequent accelerations and decelerations due to urban traffic circumstances and many stoppings for loading/unloading of goods.

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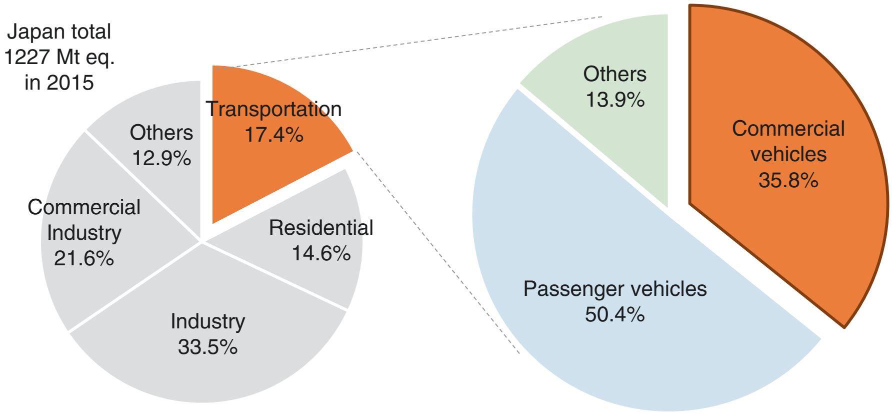


Fig. 26.1 CO_2 emissions by sector and by vehicle type in Japan [1]

Considering energy efficiency or CO_2 emissions from the aspect of “well-to-wheels” (from crude oil production through running) and energy consumption, electric vehicles (EVs) are more efficient than internal combustion engine vehicles (ICEs), because of their highly efficient motors and regenerative braking systems which recover kinetic energy at deceleration. In the future, it is also expected that EVs become CO_2-free by consuming electricity derived from renewable energy. Moreover, EVs have other excellent properties such as air pollution free, low noise emissions, etc. From the above, it can be said that EVs are more suitable for small-lot delivery than ICEs. Although passenger EVs have begun to spread, the spread of commercial EVs is lagging behind. In this research, the CO_2 emissions from micro vans both of EVs and ICEs in Japan are estimated based on the electric millage and fuel economy, respectively, in the real world. And finally we get environmental effects of micro van electrification.

26.2 Survey on Actual Use Case of Micro Vans

26.2.1 Existing Survey Report

In this paper, we refer to “Survey on Small/Light Truck Market Trends” (FY 2016) [2] and “Survey report on micro car usages” (FY 2015) [3]. Among the survey results, we employed the data of “Kei cab-over van.”

Figure 26.2 shows monthly average running distance in 2016. Less than 1200 km range takes 75% of the users. The average is 1147 km.

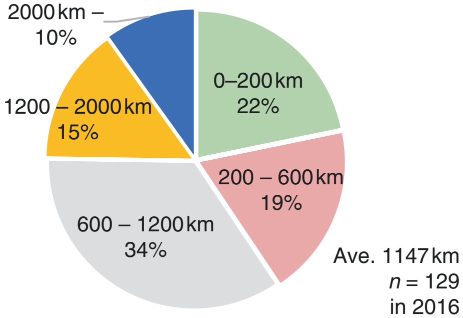


Fig. 26.2 Average running distance per month [2]

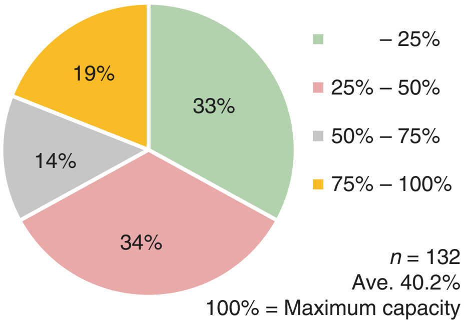


Fig. 26.3 Usual loading conditions [2]

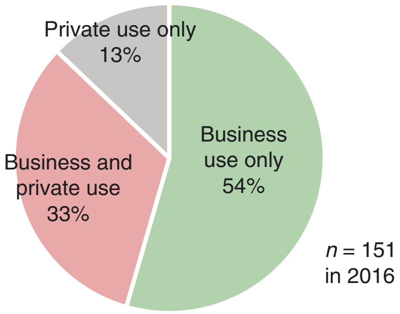


Fig. 26.4 Purpose of micro van use [2]

Figure 26.3 shows usual loading conditions. Less than 50% loading range, with respect to the maximum load 350 kg, takes 67% of the users.

Figure 26.4 shows use fields of micro vans, which include both business use and private use. Table 26.1 summarizes major uses of micro vans. Top three, named type A, B, and C, will be helpful in making our running test patterns.

According to the survey result of frequency of use [3], 74% of the users use "almost every day," and 12% use "4 to 5 days a week." If we assume 30 operating days per month, the daily running distance can be estimated about 38 km.

Table 26.1 Common uses of micro van [2]

Use type	Uses	Response rate [%]
A	Round trip to workplace	47
B	Sales or services	33
C	Door-to-door delivery service	32
–	Shopping for groceries	27
–	Transport of consigned goods	22

Note: Multiple responses allowed, n = 132, in 2016

Table 26.2 Use cases of micro van

Job category		Number of micro vans owned	Operating hours	Use type	Average driving distance per day	Traveling pattern
Small food shop		1	In the morning	A	10–20 km	A round trip to the city center
Office supplies		5	6 hours	B	65 km	Visit to 10–15 customers in town
City post office	i	31	5–6 hours	C	40 km	Visit to 50 customers in town
	ii			C(B)	60–100 km	Visit to customers in far area
	iii	4		A	60–100 km	Round trip to a local office

26.2.2 Interview for Users

We interviewed a shop and offices in Yurihonjo City, Akita Prefecture, which correspond to the top three use types in Table 26.1. The results are summarized in Table 26.2.

26.3 Estimation of Emissions from EV

In this chapter, the estimation method is developed for CO_2 emissions from an EV micro van. In the case of EVs, CO_2 emissions are proportional to electric energy consumption.

Main factors that determine the amount of energy consumption of a vehicle are running distance, speed, regeneration efficiency, acceleration/deceleration, load, and outside temperature. Among them, running distance is the primary factor. Electric mileage is defined as running distance divided by electric energy consumption. Electric energy consumed by air conditioner is also supplied from the main battery of EV. Energy consumption for heating becomes large especially in midwinter [4].

Therefore, it is a natural idea to divide the whole energy consumption of EV into two parts which are the energy required for running in a standard outside temperature without air conditioning and the energy depending on outside temperature mainly consumed by air conditioning.

26.3.1 Estimation of CO_2 Emissions from EV per Day

Equation (26.1) is for calculating CO_2 emissions from an EV micro van per day which runs in a certain *j*-region.

Depending on each region, the average speed v_j varies much. The average speed on an urban stop-and-go road with many signalized intersections is lower than the one on a rural road. The complex speed profile including various acceleration and deceleration effects the electric mileage also through regeneration efficiency and loading conditions. Therefore in this paper, the resultant average speed $v_j$takes the important role which represents the complex running conditions instead of plural mileage-effective factors.

In the first term, CO_2 emissions per km $e_{\mathrm{EV}}(v_j)$ in a standard outside temperature without air conditioning will be given in Sect. 26.3.4.

In the second term, air conditioning power consumption during a trip depends on the outside temperature of the day and is proportional to the trip time. Air conditioning power consumption $P_{\mathrm{AC}}(T_{ij})$ will be given in Sect. 26.3.5.

$$E_{\mathrm{EV}_{ij}} = L_{\mathrm{Day}} \times e_{\mathrm{EV}}\left(v_j\right) + \left(P_{\mathrm{AC}}\left(T_{ij}\right) \times \frac{L_{\mathrm{Day}}}{v_j} \times C_{\mathrm{Electric}} \right) \tag{26.1}$$

$E_{\mathrm{EV}_{ij}}$: CO_2 emissions from EV per day [kg-CO_2/day/veh]
L_{Day}: Average running distance per day [km/day]
e_{EV}: CO_2 emissions per km [kg-CO_2/km/veh]
v_j: Average vehicle speed in *j*-region [km/h]
P_{AC}: Air conditioning power consumption [kW/veh]
T_{ij}: Average outside temperature of the *i*-day [°C]
C_{Electric}: Emission factor (electric power generation) 0.516 [kg-CO_2/kWh] This is the value after adjustment of CO_2 credits, etc. in FY 2016 by the Electric Power Council for a Low Carbon Society [5]

26.3.2 Outline of Running Test to Identify e_{EV}

Introduced here is the running test to identify e_{EV}. Not only an EV micro van but also an ICE one ran together in the test. Figure 26.5 shows the two test vehicles, and Table 26.3 shows their specifications.

The test conditions are the combinations of three routes (see the next section), three loading levels (Table 26.4), and air conditioner *on/off*. The driver synchronizes the vehicle speed to the surrounding traffic flow in every route. The air blower operates at the maximum power to introduce fresh air with all the windows closed. Because the test was conducted in July, air conditioning was in cooling mode in the case of “air conditioner ON.” ICE was always in “2WD mode.”

Battery input/output power (EV power) and others were acquired through CAN (Control Area Network, typical onboard LAN) in EV.

Fig. 26.5 Test vehicles (left, EV, right, ICE)

Table 26.3 Specifications of test vehicles

	EV	ICE
Model	U68 V (battery 16 kWh)	DA17 V
Registration year	2012	2015
Motor	30 kW electrical motor	0.66 L gasoline engine
Transmission	N/A	AMT*
Energy consumption rate (JC08 Mode)	125 Wh/km (8 km/kWh)	19.0 km/L
Drive system	MR	FR-based 4WD
Curb weight	1110 kg	890 kg
Seating	4	4
Maximum load	350 kg	350 kg
Price	2,150,280 JPY	1,161,000 JPY

*Automated manual transmission (5-speed)

Table 26.4 Loading conditions

Levels	Cargo mass (without a driver)	In comparison with max. load
Light	35 kg	10%
Medium	115 kg	33%
Heavy	165 kg	47%

The energy consumption of EV is obtained as time series data by integrating EV-power. In the case of ICE, fuel consumption meter, a standard equipment of the vehicles, is employed. The meter is reset at the start, and the digits are recorded at the end of the driving.

26.3.3 Three Drive Routes

Three kinds of drive routes were arranged in Yurihonjo City with the start/goal point in our campus.

26.3.3.1 Urban Route

Urban route corresponds to "Use type C" and "Use type B" in Table 26.2. The route is 10 kilometers in length with 6 stops which average interval becomes about 1.4 kilometers, also with 24 signalized intersections. It takes about 30 min to round, and the average speed becomes 20 km/h.

In the case of ICE, the engine is stopped at six stops. This manner comes from the post office use case in Sect. 26.2.2.

26.3.3.2 Rural Route

Rural route corresponds to "Use type A." This round trip route is 13.4 km in total length without signalized intersections. It takes about 22 min to round, and the average speed becomes 38 km/h.

26.3.3.3 Expressway Route

Expressway route corresponds to "Use type A" including expressway sections. This round trip route is 58.2 km in total length with six signalized intersections and without traffic jams. It takes about 30 min to round, and the average speed becomes 56 km/h.

The driver regulates the speed not to exceed 60 km/h in general road sections and 80 km/h in expressway sections.

26.3.4 Running Test Result

Figure 26.6 compares $e_{\mathrm{EV\ and}}$ e_{ICE}, CO_2 emissions by running and air conditioning per kilometers from EV and ICE, respectively, by route and load conditions. We missed measurements in some test conditions. The available data in expressway route is only "air conditioning OFF."

CO_2 emissions per kilometers by air conditioning in urban route vary meaninglessly among loading conditions; therefore, the measurements are unreliable both in EV and ICE. In urban route, emissions by air conditioning are generally higher than in rural route. This is because the air conditioning operating time is longer due to the lower average speed than in rural route.

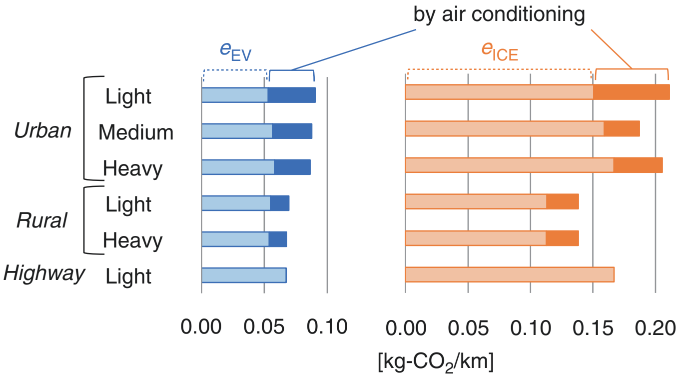


Fig. 26.6 Comparison of CO_2 emissions per kilometers between EV and ICE

Table 26.5 CO_2 emissions per kilometers of each route

Course	Average speed [km/h]	e_{EV} [kg-CO_2/km]	e_{ICE} [kg-CO_2/km]
Urban	20.0	0.0532	0.151
Rural	37.6	0.0549	0.113
Highway	56.0	0.0674	0.167

The heavier the load, the more CO_2 emissions by running. In EV, this tendency is small even in urban route, so loading conditions are neglected in e_{EV} model. However in ICE, the tendency is clear in urban route. This difference between EV and ICE is thought to be due to motor characteristics and presence or absence of regenerative brake.

Table 26.5 summarizes e_{EV} and e_{ICE} by route under light loading condition and "air conditioning OFF." In EV, the difference between urban route and rural route is small. The increment from rural route to expressway route might be caused by aerodynamic resistance. In ICE, emissions in urban route are worse than rural route. This is also thought to be due to motor characteristics and regenerative brake.

26.3.5 EV's Running Resistance

Figure 26.7 gives the running resistance curve R [N] derived from the running test in rural route and expressway route under air conditioning OFF and light loading condition in the previous section. Equation (26.2) is employed for R calculation. P [W] is measured EV-power, and v [m/s] is vehicle speed.

$$R = P / v \tag{26.2}$$

The plots in the figure are the data obtained by averaging the short (1 s) periods without acceleration, deceleration, and road gradient [6].

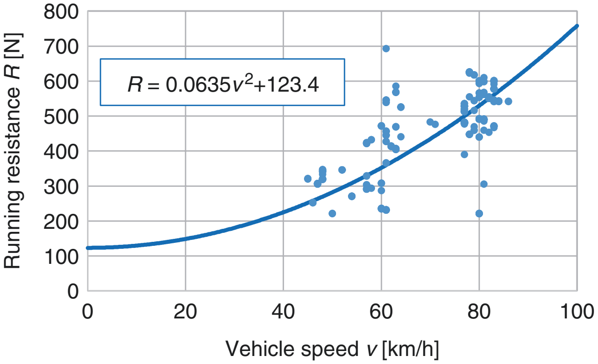


Fig. 26.7 Running resistance of the EV micro van

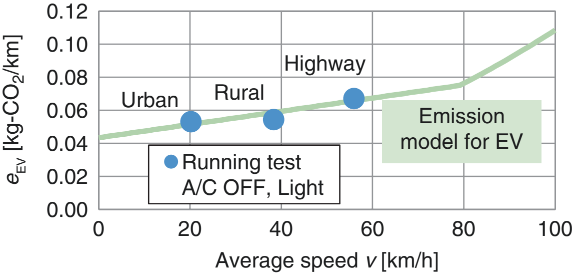


Fig. 26.8 CO_2 emission model for EV without air conditioning

Running resistance acting on a running vehicle at a constant speed on a flat road consists of rolling resistance and aerodynamic resistance. Rolling resistance is assumed to be constant with respect to vehicle speed, and for the constant, the tension is employed which was measured by pulling the EV at extremely low speed on a smooth surface. Aerodynamic resistance is proportional to the square of vehicle speed. Thus, the running resistance curve in a quadratic expression, where the first order term is zero, is approximated by the least squares method.

26.3.6 CO_2 Emission Model for EV: e_{EV}

Figure 26.8 shows the CO_2 emission model for EV without air conditioning. In the lower vehicle speed range, the linear regression model of the three measured points (●) in Table 26.5 is employed. In the high speed range, the running resistance curve (Fig. 26.7) is employed using emission factor C_{Electric}.

26.3.7 Air Conditioning Power Consumption P_{AC}

Monthly tests were conducted to investigate the power consumption that depends on outside temperature mainly by heating and cooling. The results are shown in Fig. 26.9.

Fig. 26.9 Monthly electric mileage and outside temperature

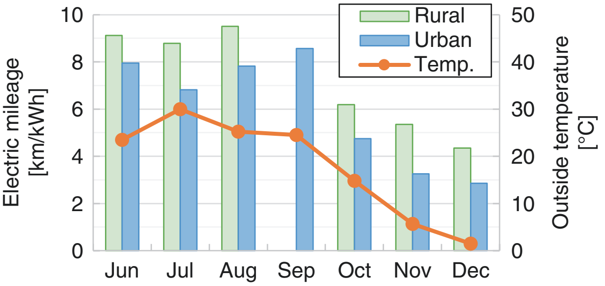
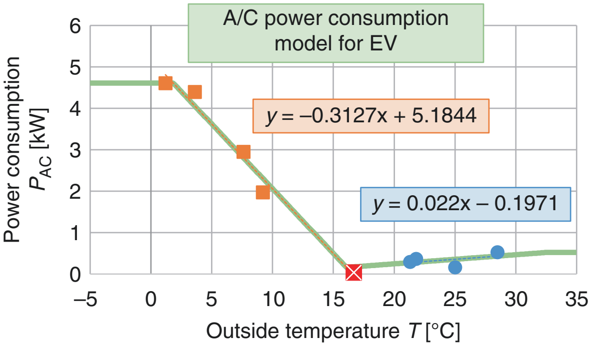


Fig. 26.10 Air conditioning power consumption model for EV



The running tests were carried out between 13:00 and 16:00 on weekdays from June to December in 2014. The maximum temperature was 30.0 °C in July, and the lowest temperature was 1.5 °C in December. The weathers were sunny or cloudy. The occupants were always a driver and a passenger. The air conditioner was adjusted to be comfortable during running. Although the power consumption by driving also varies a little seasonally, we deal with the change to be included in air conditioning power consumption.

Resultant air conditioning power consumption model P_{AC} is shown in Fig. 26.10, which consists of heating line and cooling line. These lines are provided by applying linear regression to the rural data in Fig. 26.9. The maximum power operations in heating and cooling correspond to the saturations in the range lower than 4.6 °C or higher than 33 °C.

26.4 Estimation of Emissions from ICE

26.4.1 Introducing Real-World “"e-nenp” Data

“e-nenpi (e-mileage)” is the web service provided by IID, Inc. [7] in Japan. Nationwide voluntary drivers were registered to “e-nenpi” system and upload refueling data every time. The service started in 2000. Every year, 840,000 refueling data are uploaded.

Users input “odometer distance,” “fuel supply amount,” “fuel price,” and “running situation” by their mobile phone or the like at the time of refueling. The “running situation” is selected from “mainly urban route,” “mainly rural route,” and “mainly highway route.”

Through the system, users can monitor their own fuel economy, compare them with others, become to know their ranking in each category, confirm the timing for oil change, manage maintenance costs, and find a cheaper gas station.

In the case of ICEs, it might be better to utilize this big data reflecting a wide variety of use cases rather than to construct an estimation model based on test car data to estimate the whole emissions in Japan.

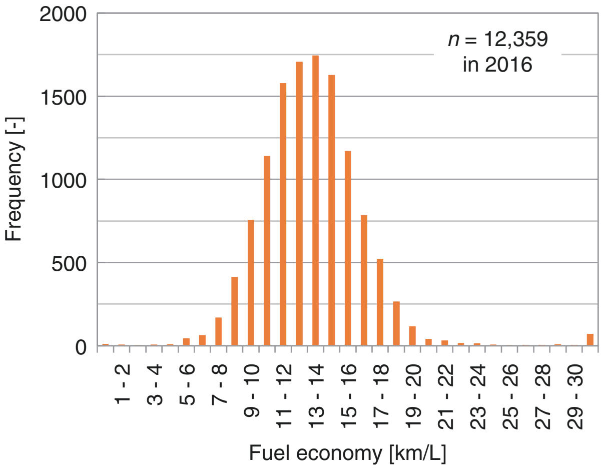
26.4.2 “e-nenpi” Data Analysis of ICE Micro Vans

“e-nenpi” data of micro vans (all are ICEs) in 2016 are analyzed. 12,359 times refueling data and 21 micro van models are included. Figure 26.11 shows the frequency distribution of fuel economy. The mode is the range of 13 to 14 km/L, and the average is 13.70 km/L. The upper 80% is included in the range of 10 to 17 km/L.

Figure 26.12 shows average fuel economy with standard deviation by driving situation. 54% are urban routes, 41% are rural routes, and 5% are highway routes. The data number is 3372 by 148 users, excluding ineligible data.

Urban routes bring the worst fuel economy. On the contrary, the best is achieved in rural routes. This is due to the low frequency of starting and stopping and the short idle time. Although the same situation is also true in expressway routes, the fuel economy gets worse because of the large aerodynamic drag caused by the higher average speed.

Fig. 26.11 Fuel economy of ICE micro vans



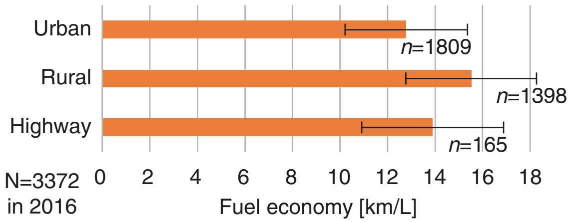


Fig. 26.12 Fuel economy by driving situations

26.4.3 Estimation of CO_2 Emissions from ICE per Day

Equation (26.3) calculates CO_2 emissions from an ICE micro van per day running in a certain *j-region*, where e_{ICE} is CO_2 emissions per km (described in Sect. 26.4.4) and c_{month} is the monthly fuel economy factor (described in Sect. 26.4.5).

The basic amount of CO_2 emissions from ICE is a product of running distance and fuel economy. As same as electric mileage of EV, fuel economy is influenced by vehicle speed, frequency of acceleration and deceleration, and so on. In addition, the amount of CO_2 emissions is multiplied by monthly fuel economy factor which reflects the outside temperature effects such as consumed power by cooling compressor and engine efficiency.

$$E_{\mathrm{ICE}_{ij}} = L_{\mathrm{Day}} \times e_{\mathrm{ICE}}\left(v_j\right) \times c_{\mathrm{month}} \tag{26.3}$$

$E_{\mathrm{ICE}_{ij}}$: CO_2 emissions from ICE per day [kg-CO_2/day/ veh]
e_{ICE}: CO_2 emissions per km [kg-CO_2/km/veh]
c_{month}: Monthly fuel economy factor [−]

26.4.4 CO_2 Emission Model for ICE: e_{ICE}

Figure 26.13 shows the CO_2 emission model for ICE, e_{ICE} curve with respect to average speed, where the gasoline emission factor is 2.322 kg-CO_2/L [8].

Because there is neither vehicle speed information in “e-nenpi” data nor published ICE microvan fuel economy curve, the curve in Fig. 26.13 is introduced by modifying the curve of a 1.5 L van [9]. As the correction factor between micro vans and 1.5 L light vans, the ratio of the average fuel economy of “e-nenpi” data and 1.5 L light van data is used.

Since those data are insufficient in the high vehicle speed range over 80 km/h, the quadratic curve calculated from aerodynamic drag is applied. This is because the aerodynamic drag is dominant in the higher vehicle speed range. Because all micro vans have almost the same appearance, the aerodynamic drag coefficient of EV in Fig. 26.7 is used.

For reference, three points of ICE in Table 26.5 are indicated with (*x*). The CO_2 emissions of ICE test vehicle are lower than the e_{ICE} model curve, because the test vehicle is the latest model with better fuel economy and in “air conditioning OFF” condition. Conversely, an e-nenpi data includes vehicles of various use years and usage of air conditioner.

Fig. 26.13 CO_2 emission model for running resistance (ICE)

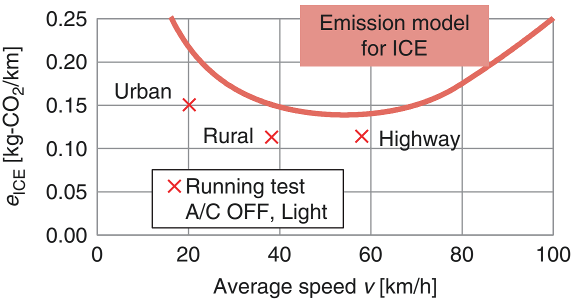
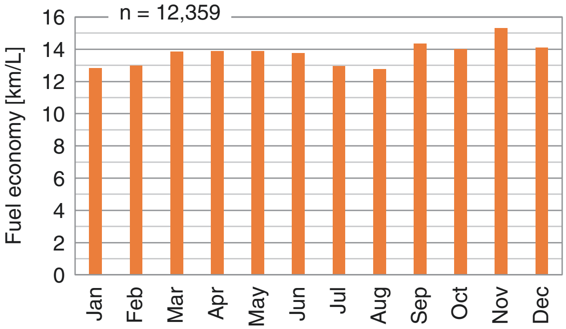


Fig. 26.14 Seasonal variations in fuel economy



26.4.5 *Influence on Fuel Economy by Outside Temperature*

Figure 26.14 shows the monthly national average of e-nenpi data. The good fuel consumptions are seen when air conditioning is not needed. The lowest is in August, which must be the cooling effect. The decline tendency is also seen in the midwinter season. It is considered that they come from warm-up operation, reduced engine efficiency, and winter tire.

From this seasonal variation in fuel economy, monthly fuel efficiency coefficient, c_{month}, is calculated.

26.5 Annual CO_2 Reduction Estimation in Japan

26.5.1 *Supplementary Data for Nationwide Aggregation*

In order to reflect the usages of micro vans in the various areas in Japan, "Traffic Census" by MLIT [10] and weather data by the Japan Meteorological Agency are applied.

"Traffic Census" is the survey of the traffic characteristics throughout Japan. In this study, we referred travel speed and traffic volume of number of normal-size vehicles* from "Traffic Census FY2015." The investigation sections are defined basically with an entrance/exit of an expressway or intersections of a main road.

The number of survey sections is 97,139, and the data of 93,096 sections are employed where the number of vehicles passing through and the travel speed are available.

From the weather data, the actual average temperature T_{ij} of i-day in 2016 at the prefectural capital to which prefecture j-section belongs is used for Eq. (26.1).

*Vehicles are divided into large and normal size in the survey.

26.5.2 Annual CO₂ Emission Estimation for EV

Equation (26.4) calculates the annual CO_2 emissions of an EV micro van running in j-section, making summation of E_{EV_j} (CO_2 emissions for running and air conditioning) during 366 days in 2016. Equation (26.5) is developed from Eq. (26.4) of an EV in j-section into all the micro vans in Japan. As the weighting for each j-section, the number of normal-size vehicles passing through the section during 24 h is used.

$$E_{\mathrm{EV}_j} = \sum_{i=1}^{366} E_{\mathrm{EV}_{ij}} \tag{26.4}$$

$$E_{\mathrm{EV}} = \sum_{j=1}^{j_{\mathrm{All}}} \frac{n_{\mathrm{S}j} \times N_{\mathrm{Van}}}{n_{\mathrm{S_{All}}}} E_{\mathrm{EV}_j} \tag{26.5}$$

E_{EV_j} : Annual CO_2 emissions in j-section (EV) [kg-CO_2/veh]

j_{All}: Number of data available sections: 93,096 [veh]

$n_{\mathrm{S}j}$: Number of normal-size vehicles passing through the section during 24 h [veh]

$n_{\mathrm{S_{All}}}$: Number of normal-size vehicles passing through all the sections during 24 h: 867,318,022 [veh]

N_{Van}: Number of micro vans in Japan: 28,764,000 [veh]

26.5.3 Annual CO₂ Emission Estimation for ICE

Equation (26.6) calculates the annual CO_2 emissions of an ICE micro van running in j-section, making summation of monthly CO_2 emissions during 12 months. Equation (26.7) is developed from Eq. (26.6) as same as Eq. (26.5).

$$E_{\mathrm{ICE}_j} = \sum_{\mathrm{month}=1}^{12} E_{\mathrm{ICE}_{ij}} \times d \tag{26.6}$$

$$E_{\text{ICE}} = \sum_{j=1}^{j_{\text{All}}} \frac{n_{\text{S}j} \times N_{\text{Van}}}{n_{\text{S}_{\text{All}}}} E_{\text{ICE}_j} \tag{26.7}$$

E_{ICE_j} : Annual CO_2 emissions in *j*-section (ICE) kg-CO_2/veh]
d: Number of days in a month [days]
E_{ICE}: Annual CO_2 emissions (ICE) [kg-CO_2/veh]

26.5.4 Annual CO_2 Emissions from EV Micro Vans and ICEs in Japan

The annual CO_2 emissions from EVs, when all ICE micro vans in Japan are replaced with EVs, are estimated by Eq. (26.5). The annual CO_2 emissions from the current ICE micro vans in Japan are estimated by Eq. (26.7). The results are shown in Fig. 26.15.

In the case of EVs, the CO_2 emissions from running are 2857 kt, and the emissions from air conditioning are 569 kt. They total to 7807 kt. The current ICE annual CO_2 emissions were 7807 kt. Therefore, micro vans electrification can reduce 4950 kt (63%). This corresponds to 5.7% of emissions from commercial vehicles. In spite of the less registered number of micro vans, only 6.0% in four-wheeler vehicles, it is estimated to reduce 3.5% emissions of the transportation sector in Japan. To attain the same reduction by improving ICEs, all ICEs should achieve 37.4 km/L which is 2.73 times the current level (13.70 km/L from "e-nenpi").

For reference, the annual nationwide amount of CO_2 emissions in JC08 mode is also shown in Fig. 26.15. EV (JC08*) is calculated by applying the published JC08 mode electric mileage of the EV test vehicle. ICE (JC08) is calculated by applying the published fuel economy of the ICE test vehicle.

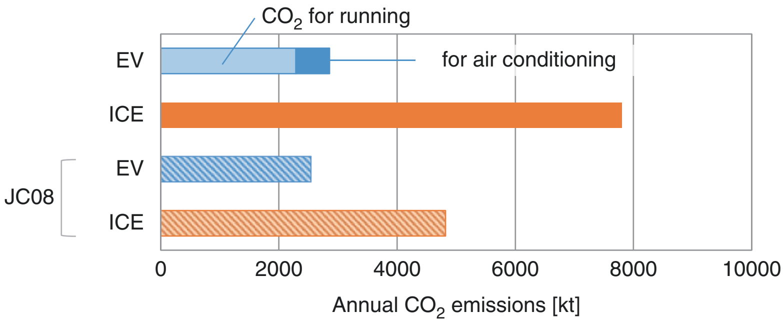


Fig. 26.15 Estimation of annual CO_2 emissions from micro vans in Japan

It can be said that the difference is rather small between EV (by Eq. (26.5)) without air conditioning and EV (JC08). On the contrary, the difference between ICE (by Eq. (26.7) using "e-nenpi" data) and ICE (JC08) is very big. There are some reasons: "e-nenpi" data include vehicles of various use years; the influence of air conditioning and loading is not taken into consideration in the JC08 mode; and the running pattern in JC08 mode may not be as strict as the reality. And it is strongly suggested that the energy efficiency of ICEs deteriorate much in the driving pattern with high frequency of starting and stopping.

*JC08: The current Japanese driving mode for fuel economy or emission measurements for certifications. The average speed is 24.4 km/h, the maximum speed is 81.6 km/h, the required time is 1204 s, the running distance is 8.172 km, and air conditioning is always OFF without loading.

26.6 Conclusions

As the environmental effect by electrification of micro vans used in Japan, it is estimated to reduce annual CO_2 emissions by 4950 kt or 63%. Since the estimation involves important factors which reflect the real-world conditions, the estimation results are much more realistic than those calculated from JC08 mode values.

The estimated annual CO_2 emissions of ICE based on "e-nenpi" becomes 1.6 times JC08. There are some reasons: "e-nenpi" data include vehicles of various use years; the influence of air conditioning and loading is not taken into consideration in the JC08 mode; and the running pattern in JC08 mode may not be as strict as the reality. And it is strongly suggested that the energy efficiency of ICEs deteriorates much in the driving pattern with high frequency of starting and stopping.

Currently in Japan, the driving mode for the certified fuel efficiency measurement is shifting from JC08 mode to WLTC (Worldwide harmonized Light duty driving Test Cycle), which is said to be close to a real world [11]. We would like to pay attention to the difference in electric mileage and fuel economy measured by WLTC mode compared with our estimation.

The air conditioner using PTC heater is popular in EVs, but the electric mileage deterioration in winter is a big problem. For example, the electric mileage of the EV test vehicle in September, installed with a PTC heater, is 2.8 times that in December (urban route data in Fig. 26.9). However, even with the current heater power consumption, the emissions from air conditioning remained only 26% against the emissions from traveling throughout Japan and throughout the year.

Attention is paid to the test result simulating the goods delivery in urban route, which is a typical use of micro vans. In the case of ICE, fuel economy is sensitive to cargo load, while in the case of EV, it is little. This sensitivity difference between EV and ICE would be mainly caused by motor characteristics and regenerative braking.

In this paper we focused only on the environmental impacts of electrification. Moreover EVs have other advantages such as air pollution free, control easiness, and low noise. Thus the authors strongly recommend the electrification in micro vans.

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Chapter 27
Describing Diffusion Scenarios for Low-Carbon Products Using Life Cycle Simulation

Kohei Saiki, Yusuke Kishita, and Yasushi Umeda

27.1 Introduction

The deployment of low-carbon products, such as PV (photovoltaic) panels and EV (electric vehicles), is rapidly growing to achieve a low-carbon society. From a long-term perspective, future changes in various factors, such as product price and product lifetime, will influence the diffusion of low-carbon products. Until now, research has been conducted on the forecasting of product diffusion [1, 2] and life cycle assessment (LCA) for estimating the environmental impact of the entire life cycles of low-carbon products [3]. However, it has not been fully studied how low-carbon products will reduce regional CO_2 emissions over a longer period of time (e.g., 30 years). To address this problem, we need to analyze the impact of future changes (e.g., energy policy, lifestyle, and technological advancement) on the diffusion of low-carbon products. It is also a challenge to look at the dynamic flow of product life cycles, which is caused by various life cycle options such as reuse, remanufacturing, and maintenance. Nowadays, these options attract much attention to foster the concept of circular economy in Europe [4]. Nevertheless, their influence on economic and environmental sustainability has yet to be examined.

The objective of this paper is to describe diffusion scenarios for low-carbon products in order to analyze the relationship among various future changes, the diffusion of the products in a region, and the regional CO_2 emissions due to product diffusion in a systematic manner. In this paper, a diffusion scenario refers to a consistent story describing the relationship among possible future situations, the diffusion of low-carbon products, and environmental impacts (e.g., CO_2 emissions) due to the diffusion of low-carbon products. For quantitative evaluation, we employ life

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cycle simulation (LCS) [5]. LCS is characterized by being able to conduct the dynamic simulation of product life cycles. Of various low-carbon products, the focus of this paper is on photovoltaic (PV) panels because PV is already widely used to generate electricity while emitting no CO_2 emissions in the use phase. In addition, we focus on CO_2 emissions as a representative indicator of environmental load in order to combat climate change.

The rest of this paper is structured as follows. Section 27.2 presents current conditions about diffusion of low-carbon products in Japan and gives a literature review on related work. Section 27.3 develops a method for describing diffusion scenarios for low-carbon products. Section 27.4 shows a case study of PV diffusion scenarios for the Tokyo area. Section 27.5 discusses the effectiveness and challenges of the proposed method. Section 27.6 concludes the paper.

27.2 Diffusion of PV Panels for Sustainability

27.2.1 Diffusion of PV Panels in Japan

The PV installation in Japan has been rapidly increasing since the feed-in tariff (FIT) scheme was enforced in 2012 [5]. Before the FIT scheme, the subsidy for household PV was terminated in 2006, and the PV installation slowed down. However, the installation increased again as the subsidy resumed in 2009. Of all PV installations, many were for residential use, whereas those for nonresidential systems accounted for about 1 to 20% [5]. Since the FIT scheme started in 2012, the introduction of PV installation has been rapidly increasing. The installation for nonresidential use accounted for about 74% in 2013 [5] because the FIT scheme enables large-scale PV systems to generate more economic profit by selling electricity to power grids. There is still much potential of PV installation for residential use, such as rooftop PV in stand-alone houses [5].

27.2.2 Literature Review

Much research has been conducted to estimate the future diffusion of PV and the environmental impact of PV diffusion throughout their life cycles. Kishita and Umeda [6] analyzed the future installation capacity of PV by taking a scenario design approach. Elshkaki and Graedel [7] investigated the demand for metals due to the development of cleaner technologies using dynamic material flow model. Peeters et al. [8] proposed a method for forecasting the material composition of waste from PV using reliability engineering.

Regardless of many related studies as partially listed above, when we attempt to create diffusion scenarios for low-carbon products, there are two major problems to be addressed. Firstly, the influences of future uncertain factors are unclear. It is difficult to predict the impact of social changes in the medium and long run on the diffusion of low-carbon products. Examples of uncertain factors include energy policy, technological advancement, and customers' lifestyle. Existing studies have not sufficiently clarified how such uncertain factors would affect product diffusion and product life cycle flows. Secondly, the relationship among the product diffusion in a region, product life cycle flows, and regional CO_2 emissions due to PV diffusion in a longer period of time (e.g., 30–50 years) has not yet sufficiently been analyzed. The diffusion of products and product life cycle flows mutually influence each other. For example, a change in consumers' preferences may accelerate the adoption of secondhand PV panels, which decreases demand for new products.

27.3 Method for Describing Diffusion Scenarios for Low-Carbon Products

27.3.1 Approach

Aiming to solve the two problems mentioned in Sect. 27.2.2, we compose diffusion scenarios for low-carbon products by taking the following approach.

Firstly, we assume possible future changes related to product diffusion and product life cycles, such as material price, product lifetime, FIT price, and product performance. Secondly, by drawing on life cycle simulation [9], we develop product diffusion life cycle model for simulating the dynamic interaction between product diffusion, product life cycles, and regional CO_2 emissions caused by product diffusion (see Fig. 27.1). The advantage of this model is to enable the dynamic simulation

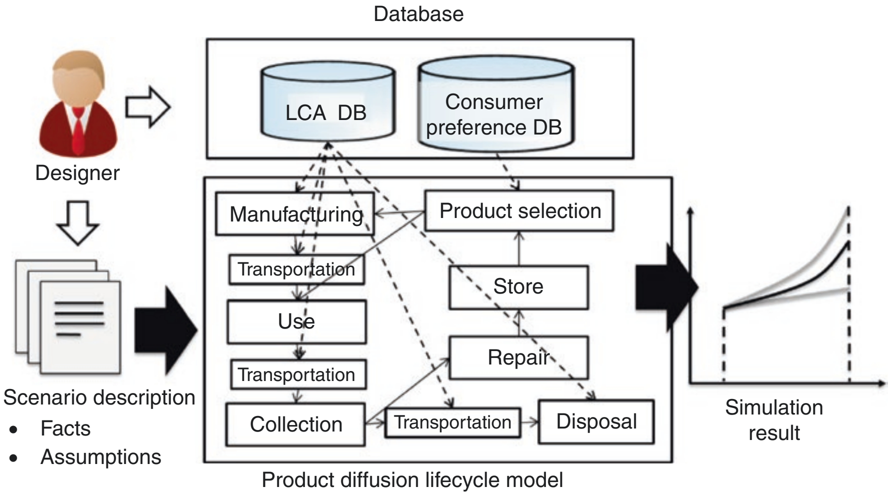

Fig. 27.1 Architecture of product diffusion life cycle model

of product life cycles by defining seven process types (e.g., manufacturing, use, and reuse; see Sect. 27.3.3 for details). To estimate the number of new purchase of low-carbon products, we implement Bass model [10] and the consumers' preference model [11] on life cycle simulator (see Sect. 27.3.2).

27.3.2 Life Cycle Simulator

Life cycle simulator [9] is a modeling environment to evaluate entire product life cycles by describing product life cycle flows, definition of input and output parameters, and procedures of each process. In life cycle simulator, a product is defined as an object containing attributes, such as constituent materials, price, and lifetime. To express behavioral changes in a product life cycle, life cycle simulator enables the designer to describe temporal changes in various attribute values in each process throughout the life cycle flow.

27.3.3 Product Diffusion Life Cycle Model

In order to evaluate future diffusion of low-carbon products and resulting environmental impacts, we develop product diffusion life cycle model using life cycle simulator [9]. The architecture of the model is illustrated in Fig. 27.1. To ensure the applicability of our method to any low-carbon product, we represent a product life cycle by defining eight types of processes as follows:

- Product selection: assumes that each consumer makes a decision about whether they buy a new product or a secondhand one.
- Manufacturing: generates product objects in response to consumers' demand for new products. This process includes raw material production, part production, and product assembly.
- Use: keeps product objects in use by consumers.
- Collection: takes back product objects that are discarded by consumers because they no longer work due to failure.
- Disposal: landfills used products (i.e., disposes product objects) that are not reused by consumers.
- Repair: restores collected products to prolong their lifetime.
- Store: stores repaired products in the warehouse until they are sold to consumers as secondhand ones.
- Transportation: transports each product from one process to another (e.g., from manufacturing to use).

By referring to the LCA database, we calculate the environmental load (i.e., CO_2 emissions) in each process such as manufacturing, transport, use, and disposal.

Given that $E_p(t)$ is the environmental load in process p at year t, the environmental load $E(t)$ throughout the life cycle at year t is obtained by the following equation:

$$E(t) = E_{\text{manufacturing}}(t) + E_{\text{use}}(t) + E_{\text{transportation}}(t) + E_{\text{disposal}}(t) \tag{27.1}$$

Details of formulating these processes are explained below.

27.3.3.1 Product Selection Process

In the product selection process, purchasers of potential products are divided into (1) new purchasers and (2) purchasers who replace old products with new ones. We calculate the number of new purchasers using product diffusion model, which was developed based on Bass model [10]. Then, based on the consumer preference database, these potential buyers (i.e., (1) and (2)) will make either of three decisions, i.e., buying a new product, buying a secondhand product, or buying nothing.

We calculate the utility (preference) of a consumer for the product in order to determine which action the consumer will take (i.e., either of actions Eqs. (27.1)–(27.3) having the largest utility is chosen). The utility of consumer i for product k is defined as follows:

$$U(i,k) = \sum_j w(i,j) \times s(j,k) \tag{27.2}$$

where j is an attribute of product k, $w(i, j)$ is the weighting factor of consumer i for attribute j, and $s(j, k)$ is the value of attribute j of product k. Examples of attribute j include initial price, running cost, and lifetime.

It should be noted that the consumer preference database (see Fig. 27.1) stores data on weighting factors in Eq. (27.2), which are obtained from questionnaire surveys.

27.3.3.2 Manufacturing Process

Product objects are produced in the manufacturing process. Several attribute values, such as lifetime and initial price, are given to each product. The number of products produced in each year is determined by calculating that of new purchasers in the product selection process. The environmental load due to manufacturing is calculated by the following equation:

$$E_{\text{manufacturing}}(t) = I_{\text{manufacturing}} \times \text{new}(t) \tag{27.3}$$

where $I_{\text{manufacturing}}$ is the CO_2 emission intensity in manufacturing products and new (t) is the number of new products manufactured in year t.

27.3.3.3 Use Process

The use process calculates annual change in the stock of products in use, including installation, failure, and degradation. We express the relationship between in-use stock and in- and outflows as follows:

$$S(t) = S(t-1) + F_{\text{in}}(t) - F_{\text{out}}(t) \tag{27.4}$$

where $S(t)$ is the number of products in use at year t and $F_{\text{in}}(t)$ is annual demand for the target product at year t and formulated as follows:

$$F_{\text{in}}(t) = \text{new}(t) + \text{secondhand}(t) \tag{27.5}$$

where secondhand(t) is the number of secondhand products sold in year t. Both values of new(t) and secondhand(t) are determined in the product selection process. $F_{\text{out}}(t)$ represents the number of products that are disposed by consumers due to failure. Here, we estimate $F_{\text{out}}(t)$ using Weibull distribution, which is frequently used in reliability engineering [8]. In year t, each product in the use process fails with a probability of $\lambda(t)$. Therefore, $F_{\text{out}}(t)$ is counted as the number of failed products. Probability density function $f(t)$ is defined along with Weibull distribution as follows:

$$f(t) = \frac{m}{\eta}\left(\frac{t}{\eta}\right)^{m-1} \exp\left(-\left(\frac{t}{\eta}\right)^{m}\right) \tag{27.6}$$

where m and η are shape parameter and scale parameter, respectively. Cumulative distribution function $F(t)$ of Weibull distribution equals the temporal integration of $f(t)$, which represents the unreliability of a product after t-year use. Given $f(t)$ and $F(t)$, the failure rate $\lambda(t)$ is formulated as follows:

$$\lambda(t) = \frac{f(t)}{1-F(t)} = mt^{m-1} / \eta \tag{27.7}$$

We assume that the shape parameter is determined based on empirical data. When shape parameter and the average lifetime of a product are given, the scale parameter is determined as follows:

$$\eta = \mu / \Gamma\left(1 + \frac{1}{m}\right) \tag{27.8}$$

where μ is average lifetime and $\Gamma(x)$ is Gamma function, which is defined as:

$$\Gamma(x) = \int_0^{\infty} t^{x-1} e^{-t} dt \tag{27.9}$$

In the use process, the reduction of environmental load (E_{use}) is evaluated by comparing the case where low-carbon products are used with the case where low-carbon products are not introduced.

27.3.3.4 Collection Process

In the collection process, the reusability of products collected from consumers is evaluated. We define the remaining lifetime of product k (i.e., RT (k)) as

$$\text{RT}(k) = L(k) - T(k) \tag{27.10}$$

where $L(k)$ and $T(k)$ are the life span of product k and the time elapsed while product k is in use. If RT (k) is larger than threshold RT_{min}, product k is evaluated as reusable and repaired as a secondhand products. RT_{min} is determined as half of the lifetime.

Disposal Process.

In the disposal process, the environmental load due to the landfill of products is calculated as follows:

$$E_{\text{disposal}}(t) = I_{\text{disposal}} \times \text{dis}(t) \tag{27.11}$$

where I_{disposal} is the CO_2 emission intensity for landfill, and dis (t) is the number of products discarded at year t, which is calculated in the collection process.

27.3.3.5 Transportation Process

In the transportation process, the environmental load due to the transportation of products is calculated as follows:

$$E_{\text{transportation}}(t) = I_{\text{transportation}} \times \text{trans}(t) \tag{27.12}$$

where $I_{\text{transportation}}$ is the CO_2 emission intensity, meaning the amount of CO_2 emitted when one product is transported from one process to another by truck, whereas trans (t) is the number of products transported at year t.

27.4 Case Study

27.4.1 Problem Setting

We described PV diffusion scenarios toward 2045 for the Tokyo area. In order to investigate the range of the diffusion of PV and the environmental impacts due to PV diffusion, we created four scenarios (i.e., baseline scenario and three derived scenarios) in which we evaluated PV installation capacity and life cycle CO_2 emissions. We conducted sensitivity analysis to extract critical factors to CO_2 emissions.

27.4.2 Calculating Solar Power Generation and CO2 Emissions in the Use Process

In the use process, we formulated the amount of electricity generated by PV, the amount of CO_2 reduction, and the decrease in electricity generation due to the deterioration of PV panels.

Assuming that $G(k, t)$ is the annual solar power generation of product k at year t in the use process, the annual electricity generation $G(t)$ at year t is as follows:

$$G(t) = \sum_i G(k,t) \tag{27.13}$$

Given that the CO_2 emission intensity of grid electricity generation is I_{grid}, the effect of CO_2 reduction due to PV use at year t is evaluated as follows:

$$E_{\text{use}}(t) = -I_{\text{grid}} \times G(t) \tag{27.14}$$

We assume that PV generation decreases due to deterioration at a fixed rate year by year. Assuming that the rate is q, the PV generation by product i at year $t + 1$ (i.e., $G(i, t + 1)$) is formulated below:

$$G(i,t+1) = (1-q) \times G(i,t) \tag{27.15}$$

27.4.3 Data Gathering

27.4.3.1 Data Sources

We conducted literature reviews to gather information for determining parameters used for the case study. In addition, we conducted a questionnaire survey on purchasing PV for consumers across Japan (560 samples) [6] and conjoint analysis in order to determine the weighting factors for calculating utility, which is defined in Eq. (27.2).

27.4.3.2 Consumer Preference Data

For calculating the utility function of PV in Eq. (27.2), we adopted three attributes, i.e., initial cost, annual energy cost reduction, and manufacturer's warranty period. Therefore, the utility $U\ (i,\ k)$ for potential purchaser i for product k is given as follows:

$$U\left(i,k\right)=W_{\mathrm{IC}}\left(i\right)\times \mathrm{IC}\left(k\right)+W_{\mathrm{RD}}\left(i\right)\times \mathrm{RD}\left(k\right)+W_{\mathrm{WT}}\left(i\right)\times \mathrm{WT}\left(k\right) \qquad (27.16)$$

where IC(k),RD(k), and WT(k) are the initial cost, annual energy cost reduction, and manufacturer's warranty period of product k, while $W_{\mathrm{IC}}(i)$,$W_{\mathrm{RD}}(i)$, and $W_{\mathrm{WT}}(i)$ are their respective weighting factors for purchaser i.

Table 27.1 shows the results of conjoint analysis based on the questionnaire survey, showing the average weighing factors of the three attributes.

27.4.4 Assumed Scenarios

We described four scenarios, i.e., (A) baseline scenario and three derived scenarios (B–D) as follows. The parameter settings of each scenario are shown in Table 27.1.

(a) Baseline scenario: The initial price of PV produced after 2030 decreases from 1858 thousand JPY to 565 thousand JPY, and the lifetime of PV is 30 years, while it is 20 years in 2016.
(b) Higher PV system price scenario: The unit PV system price increases due to a higher price of raw materials (e.g., silicon) to produce PV.
(c) Lower fuel price scenario: Since the fossil fuel price rises, grid electricity price increases.
(d) Longer lifetime scenario: System unit price of PV decreases, and lifetime extends due to technological innovation.

In Table 27.2, parameter settings of each scenario are shown. In Scenario B, the initial price of PV is 1.5 times higher than in Scenario A. In Scenario C, the grid electricity price is 0.67 times as much as Scenario A. In Scenario C, the lifetime of PV is 35 years, while it is 30 years in Scenario A. We calculated potential diffusion rates for scenarios A–D based on the questionnaire survey [6].

Table 27.1 Conjoint analysis result from the questionnaire survey [6]

Attribute j	Weighting factor w_{ij}	
	Mean value	Unit
Initial cost of PV	−0.00259	Point/thousand JPY
Reduction of annual utility cost	0.02472	Point/thousand JPY
Length of warranty	0.0947	Point/year

Table 27.2 Parameter settings for each scenario

Parameter	Unit	2016	2030–2045			
			A	B	C	D
Product						
Unit installation capacity	kW/unit	–	4.3			
Initial price [5]	Thousand JPY/unit	1858	565	848	565	516
Lifetime [5]	Year	20	30			35
Shape parameter [12]	–	–	5.3759			
Scale parameter (Eq. 27.8)	–	21.7	32.54			37.96
CO$_2$—Manufacturing [13]	Kg-CO$_2$/unit	4360				
CO$_2$—Transportation [13]	Kg-CO$_2$/unit	84				
CO$_2$—Disposal [13]	Kg-CO$_2$/unit	14				
Product diffusion model						
Potential diffusion rate	%	–	57.5	39.3	56.4	59.3
Innovation coefficient	–	–	0.014934	0.020304	0.014427	0.013749
Imitation coefficient	–	–	0.3005	0.3255	0.2983	0.2954
Grid electricity price	JPY/kWh	24.6	27.0		24.6	27.0
FIT price	JPY/kWh	38	18.5			
Reduction of electricity cost	Thousand JPY/year	158	113		108	113
Cost payback time	Year	11.7	5.02	7.5	5.2	4.6
Reusable remaining lifetime	Year	10	15			17.5
CO$_2$ emission factor for grid electricity generation	Kg-CO$_2$/kWh	–	0.5335			

27.4.5 *Simulation Results*

27.4.5.1 PV Installation Capacity

Figure 27.2 shows the running capacity of PV. The PV capacity and diffusion rate (i.e., number of households owning PV panels to all households) in 2045 are 14.5 GW and 55.4% in longer lifetime scenario, 14.0 GW and 53.6% in baseline scenario, 13.8 GW and 52.7% in cheaper fuel price scenario, and 9.6 GW and 36.8% in higher system price scenario.

Figure 27.3 shows the annual installation capacity in baseline scenario, in which the number of new purchasers is the largest in 2025 and then gradually decreases. As the annual amount of failure of products begins to increase from around 2025, the installation capacity by replacement increases. The total PV installation drops in 2035 and then increases again. In 2045, the installation by new purchaser almost saturates, where most of PV purchase is attributed to replacement.

Figure 27.4 shows the annual installation by product type in baseline scenario, in which the amount of secondhand PV increases from around 2035. In 2045, secondhand

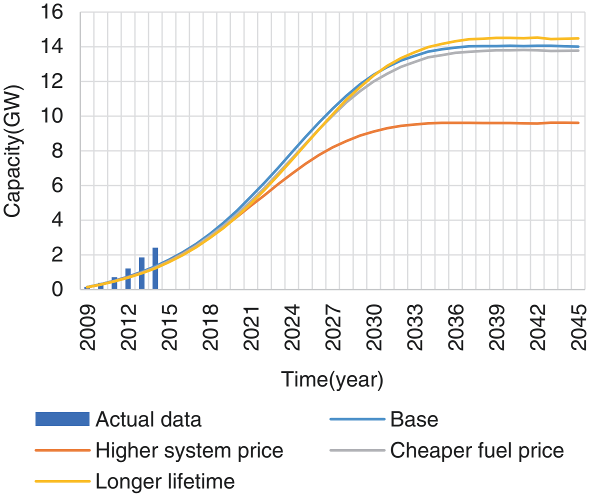

Fig. 27.2 Running capacity of PV

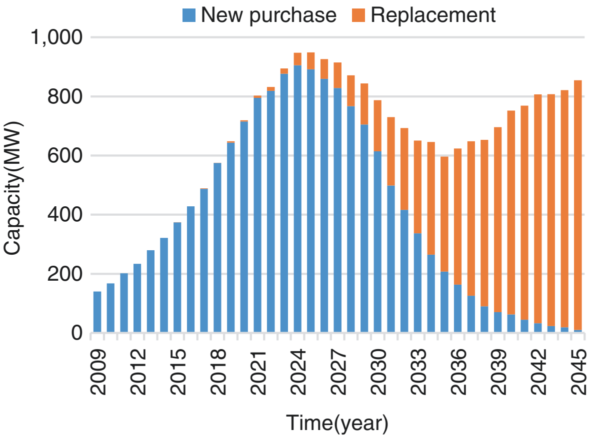

Fig. 27.3 Annual installation by purchaser type in baseline scenario

PV accounts for 8.3% of the annual installation. In the long-life scenario, the installation amount of secondhand products is 18.6%, which is the largest of four scenarios.

27.4.5.2 Annual CO_2 Emissions Due to PV Diffusion

Figure 27.5 shows the annual CO_2 emissions due to PV installation. The annual CO_2 emissions are negative throughout the period of concern since the amount of reduction of CO_2 emissions in use process exceeds the CO_2 emissions in the manufacturing, transportation, and disposal processes.

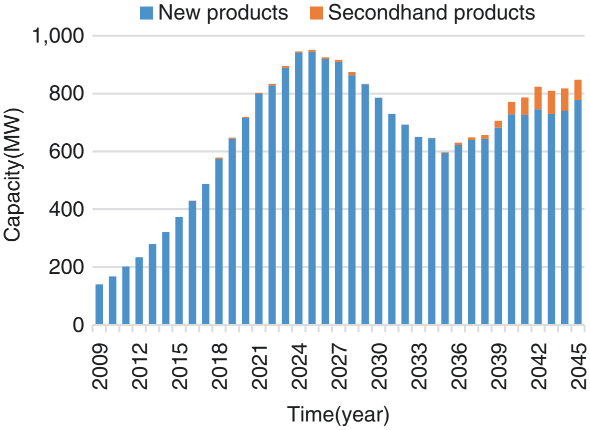

Fig. 27.4 Annual installation by product type in baseline scenario

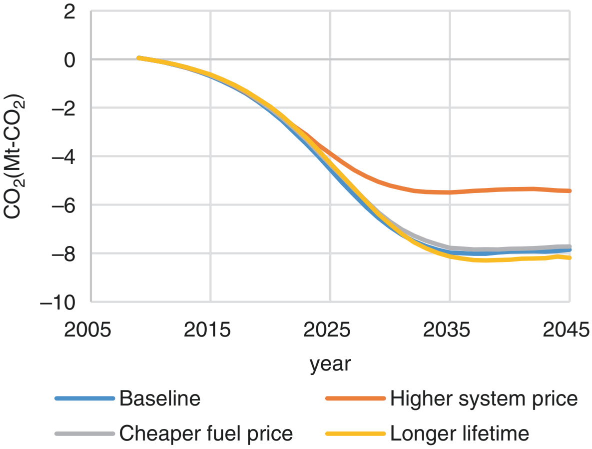

Fig. 27.5 Annual CO_2 emissions due to PV generation

27.4.6 Sensitivity Analysis

We conducted sensitivity analysis in order to investigate the major factors that impact the cumulative CO_2 emissions due to PV installation from 2016 to 2045. The parameters of interest here are FIT price, lifetime and system unit price of PV produced after 2030, grid electricity price, and shape parameter of Weibull distribution since these seem to have a higher influence than other parameters. Sensitivity here is the percentage of a change in CO_2 emissions compared to baseline scenario when a parameter value increases by 10%. Table 27.3 shows that FIT price has the largest influence on cumulative CO_2 emissions (−21.55%). This is because an increase in FIT price has a large impact on the reduction of electricity cost, which results in more consumers to purchase PV. On the other hand, the impact of system unit price is relatively small (0.63%) because consumers feel the reduction of utility cost more valuable than initial price.

Table 27.3 Parameter settings for each scenario

Parameter	Value		Sensitivity (%)
	Original	10% increase	
FIT price (JPY/kWh)	18.5	20.35	−21.55
PV lifetime (year)	30	33	−0.92
System unit price (JPY)	13.1	14.5	0.63
Grid electricity price (JPY)	27	29.7	−2.18
Shape parameter	5.38	5.91	−0.03

27.5 Discussion

The case study results showed that the combination of descriptive scenarios and product diffusion life cycle model is workable in calculating long-term CO_2 emissions of PV panels. In particular, product diffusion life cycle model enabled dynamic life cycle flow analysis by looking at temporal changes in values of product attributes, the breakdown of installation in terms of new purchase and replacement, and the breakdown of installation of new products and used products.

The results of the scenario analysis showed that, as depicted in Scenario B, the increase of raw material prices is the most influential on PV diffusion, whereas that in electricity price is less influential as shown in Scenario C. In the baseline scenario (Scenario A), the running capacity of PV (i.e., in-use stock of PV) is saturated up to 2045. The annual installation by new purchase peaks in 2025, while the annual installation caused by replacement gradually increases beyond that point. Regarding the annual installation of secondhand PV, the ratio of products evaluated as reusable to collected products is remarkably higher than other scenarios. In 2045, the share of annual installation of secondhand PV is 18.6% in Scenario D, which is 2.2 times larger than in Scenario A (8.3%).

According to the results of sensitivity analysis in Table 27.3, the FIT scheme for PV panels is effective for the reduction of CO_2 emission, because the diffusion of PV panels is promoted due to their lower prices. In contrast, prolonging PV lifetimes and increasing grid electricity prices are less influential on PV diffusion and resulting CO_2 reduction.

There are some remaining problems to be addressed. One of them is to verify the validity of our model. For example, in Fig. 27.2, there is a gap between the curve of running capacity of PV and actual data. In the product selection process, we fitted the curve of potential purchasers (i.e., Bass model) to the actual data.

Because some of potential purchasers take the choice of not buying PV, the number of purchasers is underestimated. To improve the validity of the model, we need to modify the model and collect data on consumer preferences for more accurate estimation.

Another problem is to consider other competing technologies, such as solar water heaters and other types of PV panels, while we focused on silicon-based PV panels in this paper. Hence, it would be a research issue to integrate a consumers' technology choice model into our model.

27.6 Conclusion

In order to analyze the future diffusion of low-carbon products and their impact on environmental load of the entire life cycle, we proposed a method to create product diffusion scenarios by developing product diffusion life cycle model using life cycle simulator. The developed model enabled the dynamic analysis of product diffusion and CO_2 emissions of the entire life cycle in response to social changes in the future.

In the case study, we described PV diffusion scenarios up to 2045 for the Tokyo area. The installed capacity in 2045 is 9.4–16.5 GW, and the cumulative reduction of CO_2 emissions due to PV generation is 128–173 Mt-CO_2. The results showed that PV system unit price of PV will greatly influence the amount of installation in the future. Also, the reuse of PV is accelerated if the lifetime of PV becomes longer. Future work includes collecting more data for more accurate estimates.

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Chapter 28
Toward the Creation of an Impact Seriousness Indicator to Assist the Designer

Florian Bratec, Nadege Troussier, and Rene Diaz-Pichardo

28.1 Introduction

Designing a product raises many questions about the harmful consequences potentially induced by this activity. Issues of ethics and responsibility are at the heart of the new problems of design and use, especially with regard to sustainability issues [1]. The design of a good or service requires many decisions until the product reaches its market. Indeed, considering the choice of materials (their origin, their potential impacts, their criticality, etc.), the choice of processes to be implemented (available technologies, potential pollution, social consequences, etc.), economic choice, the choice of the logistics system to be deployed, or the choice of production sites involves directly or indirectly the designer or the project design team. Each of these decisions involves some responsibility of the designer, which varies from simple compliance with industry standards to a commitment beyond "the call of duty" [2].

Concerning the environment, the integration of responsibility into design is reflected in ecodesign. In the 1970s, the integration of the environmental performance criterion into the design process is clarified and imposed as a quality criterion [3]. This period is characterized by the development of the first methodologies to evaluate ecodesign [4]. The multiplicity of decision-making contexts, linked to the different designing organizations, has led to a fast and abundant development of tools and methods for design to the present day. On the ecodesign side, Life Cycle Assessment (LCA) has emerged as the central method to assist the designer in his environmental performance approach [5]. Indeed, Life Cycle Assessment is a

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methodology, normalized by the ISO 14040 standard, to calculate the potential environmental impacts of a good or a service throughout its life cycle: from extraction of materials to destruction of the product after use. This methodology has the advantage, among other things, of providing a broad scope of indicators, from the global impact such as the global warming potential to local impact such as freshwater eutrophication, including also regional impacts such as the creation of photochemical ozone. In addition to the geographical scale of these impacts, the indicators provided by the LCA fall into two categories: a problem-oriented category, including the midpoint impacts, and another damage-oriented category, including the endpoint impacts. Midpoint impacts are commonly representative of environmental problems: it quantifies an effect but not a consequence. A carbon dioxide emission is an environmental problem and represents a well-known midpoint impact: the global warming. The endpoint impacts are representativeness of an environmental damage, a final consequence: it could be a loss of biodiversity or the climate change (which is a consequence of the global warming).

However, although LCA is an essential tool for the modeling of environmental impacts, one of its major limitations is its lack of geographical representativeness [6]. Indeed, the geographical variability of the areas affected by an impact induces that these areas are more or less sensitive and more or less resilient considering a potential damage. This problem of representativeness complicates the decision-making of the designer because it compromises the reliability of the results of the LCA. In view of this lack of spatial sensitivity, the question of seriousness arises. Is potential environmental damage more or less serious or severe depending on where it is located? How to geographically contextualize a potential environmental impact?

Through this study, we seek to propose a pragmatic approach to the designer with the development of a seriousness indicator based on the geolocation of impacts resulting from the LCA. In this article, we focus on the impact of land use, which is strongly subject to the problem of geographical variability and no consensual model has yet been achieved on this impact category [7].

28.2 The Opportunities of Spatialization

The occurrence of an environmental impact sees its severity vary according to its location. Indeed, for example, water consumption in an arid environment will have a higher impact than in wet conditions. As a result, for obvious questions of representativeness and precision, more and more research integrating a geographical dimension into the Life Cycle Analysis is developing.

Most research is based on a link between LCA and the geographic information system (GIS). The first application of this coupling aims to spatialize the Life Cycle Inventory in order to reduce the uncertainty of the results. This approach has been tested in particular by Geyer et al. [8] in 2010 on land-use impacts. In this study, GIS made it possible to differentiate the transformations of habitats linked to the production of ethanol in California and thus to demonstrate that the impact of land use depends not only on the type of culture installed but also and especially of the induced change of occupation. Indeed, land-use modeling models focus on the type of occupation and do not sufficiently consider the information related to the context of this occupation, in particular with regard to the endured change [9]. In addition, land use is now identified as the main cause of biodiversity loss [7].

If the coupling between LCA and GIS is more accurate in the Life Cycle Inventory, a second application aims at creating new input data. In 2011, Gosal et al. [9] use this approach to determine optimal locations for biomass production, including biophysical, meteorological, and climatological data, with the aim of reducing the climate change potential resulting from this production. If the hybridization of geographic parameters and impact data can help to identify a better situation, considering the environmental issues, this approach can potentially also identify a worse situation and thus would be interesting to use to measure the severity of an impact. Nevertheless, given the spatial nature of these parameters, measuring the severity of an impact would only make sense if it occurred on a local or regional scale [10]. Global impacts, such as climate change, are not subject to spatial variability and therefore cannot be assigned a severity or seriousness indicator based on a geographical approach.

Closer to the notion of severity, it is increasingly common to observe the use of spatial data, usually via a GIS, to refine the characterization factors used in LCA. This approach is particularly observed for the quantification of acidification [11, 12], eutrophication [13], and toxicity [14, 15]. To a lesser degree, work is also being carried out on the land-use impact [16] to differentiate the characterization factors according to the location of the impact. This category of impact can be expressed at the midpoint level, as proposed by the work of Milà i Canals et al. [17], LANCA® [18], or Weidema and Lindeijer [19], but also by extension at the endpoint level in the biodiversity loss category. This last category of impact is quantified in PDF (Potentially Disappeared Fraction of species) per m^2 and per year.

Weidema and Lindeijer [19] propose to calculate the land-use impact using the following approach:

$$\text{Iocc} = A \times t_{\text{i}} \times \left(Q_{\text{pot}} - Q_{\text{act}}\right) / S_{\text{i}}$$

In this formula, A is the occupied area, t_{i} is the time of occupation, Q_{pot} is the quality indicator for the reference situation, Q_{act} is the quality indicator for the current situation, and S_{i} is a slope factor modeling the duration restoration of the reference situation. According to this model, the two-variable Q must be sensitive to the impacted environment and therefore to the geography. According to Milà i Canals et al. [17], three major parameters have to be taken into consideration when assessing the quality of the situation in relation to the impact: biodiversity, biotic production potential, and soil ecological quality. In fact, the latter two parameters are directly related in a cause-effect relationship, since the quality of a soil directly depends on the potential for biotic development, via its plant, animal, and ecosystem production capacities [20]. Thus, the severity of a land-use impact could be represented by two main parameters: the quality of the environment in terms of biotic richness and the quality of the environment in terms of resilience.

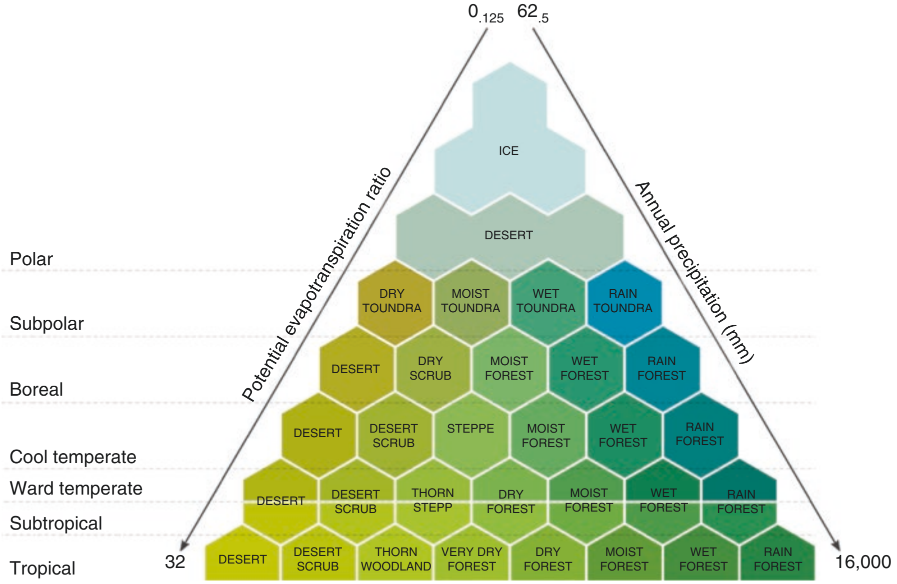

Fig. 28.1 Holdridge life zones

In this proposal, the representation of the biodiversity parameter is based on the research of Ellis et al. [21] and their global mapping of biotic richness in species per km^2. The representation of the soil quality parameter, and therefore of resilience, is based on the Holdridge life zones model [22], classifying the potential biotic development regions depending on their latitude, evapotranspiration, and precipitations (Fig. 28.1).

28.3 A Seriousness Indicator to Assist Decision-Making

Spatialization represents an opportunity to assess the seriousness of an impact in LCA, provided that it has a geographical sensitivity due to its local or regional occurrence. Assessing and even measuring the severity of an impact would then open up a new angle of interpretation for the designer, in particular to choose the geographical location of an activity or a process. In this study, the proposal focuses on a single category of impact, which is land use.

The Holdridge life zones model [22] provides a fairly fine classification of terrestrial biome types. This classification is based on the latitudinal location of the zone (from tropical to polar), annual precipitation, and evapotranspiration potential (Fig. 28.1). Depending on these parameters, 38 life zones are identified (off-ice), from super-arid to super-humid areas. For the seriousness indicator, this model was used to illustrate soil quality, depending directly on the bioclimatic parameters used

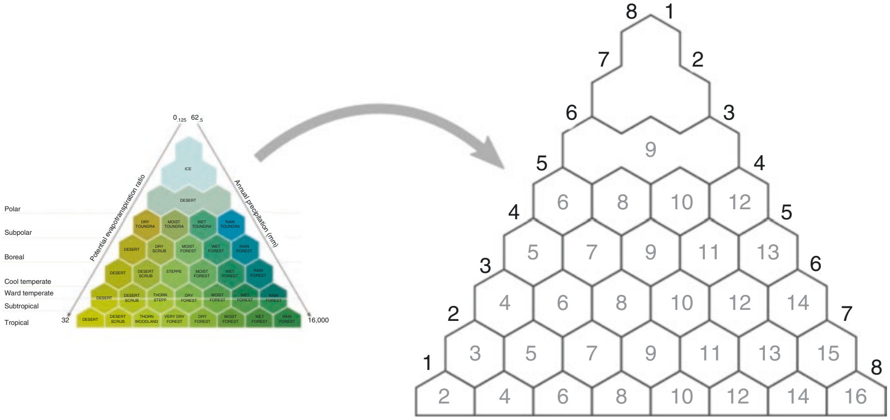

Fig. 28.2 Biotic production potential scores

Fig. 28.3 Biotic production potential scores map

and recommended by Milà i Canals et al. [17] with regard to biotic development issues. The crosses corresponding to the life zones are then converted into scores representing the potential for biotic production (Fig. 28.2).

The creation of a database gathering these scores was then carried out. By combining with the bioclimatic parameters defined by Holdridge, it was possible to locate these scores spatially. The database consists of 16,200 geographical segments per layer, which corresponds to a WGS84 projection with an accuracy of 2°. These settings allowed to obtain 2899 couples score-segment, being 2899 geographical points linked to a potential of biotic production (BPP). The result in cartographic form offers a degree of precision that is perfectible but sufficient to understand the geographical variability of this parameter (Fig. 28.3).

As regards the parameter representing biodiversity and therefore the quality of the reference situation, this proposal was based on the work and cartography of Ellis et al. [21]. In particular, they have established a global map of the density of native vascular plants. In this proposal, this work was used to produce a second database corresponding to a WGS84 projection and a 2° accuracy. Thus, 2899 other couple score-segments were obtained with this time a link established

Fig. 28.4 Vascular plant species (based on Ellis et al.)

Fig. 28.5 Seriousness indicator for land use

between the geographical points and the biodiversity of the reference situation (BRS). The database display is also available as a map (Fig. 28.4).

In order to understand the notion of seriousness due to spatial variability, four geographical locations were selected for comparison. The four types of occupation correspond to an artificial area on 1 km^2 for 1 year. The IMPACT World+ method gives a default result of 0.44 PDF for this type of land use. This score was combined with previously established databases with geographic location as the only input key. The results are represented as a radar with an impact axis in PDF (common to the four locations because it is dependent on the land-use pattern), a biodiversity axis for the reference situation (BRS), and an axis of biotic production potential (BPP) (Fig. 28.5).

In this example, four more or less different profiles appear on the map. Obviously, considering that the selected parameters are representative of the severity of the impact studied, it will be more serious to artificialize an area at location #2 than at any other location. In the same way, it seems obvious that location #3 is the best option for the designer who wants to immobilize an area for production, for example. On the other hand, the profiles of locations #1 and #4 are very similar and would require a thorough assessment. Put the title directly under the top margin. The title should be in Times 16 point bold centered. Use capitals as indicated in the title of this example. The first word of the title and all major words must start with a capital. The authors section should be in Times 10 point normal.

28.4 Conclusion

The geographical variability to which most of the impact indicators derived from the Life Cycle Assessment are subject induces a severity of the impact, which is higher or lower depending on the place of occurrence. On the land-use category, the severity of the impact can be assessed by considering the biodiversity of the reference situation, in particular with the work of Ellis et al. [21], and the biotic potential of the environment concerned. The scoring work carried out using the Holdridge model [22] and the creation of a cartographic database allowed the creation of a seriousness indicator depending on the geolocation of an occupation. This new information, in the form of a radar indicator, can assist the decision-making of the designer, who can then determine the least harmful options at his disposal in terms of land-use choices.

In this study, only the land-use indicator was addressed. This approach, for example, allows for better informed decision-making on the issues of seriousness when it comes to setting up a production site, which in particular leaves open the door to industrial and territorial ecology. This indicator can also be used to design a more responsible supply chain. Nevertheless, the development of this approach and its implementation requires the integration of other local or regional impact indicators to offer a stronger complementarity with the Life Cycle Assessment.

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