

A graphical representation for consequential life cycle assessment of future technologies—Part 2: two case studies on choice of technologies and evaluation of technology improvements

I-Ching Chen · Yasuhiro Fukushima ·
Yasunori Kikuchi · Masahiko Hirao

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Abstract

Purpose To construct future visions of how innovative technologies should be used in the envisioned sustainable society while being aware of system-wide environmental impacts, consequential life cycle assessment (c-LCA) is useful. To systematically evaluate the technologies being aware of uncertainties in the choice of technologies made in the future, in this article, we propose a novel graphical representation for theoretical range of impacts that contain results from c-LCA studies. This approach allows analyses of the consequences of technology introduction without conducting a detailed modeling of consequences.

Methods We stand on an assumption that the future environmental impacts reduced by a new technology depends on (1) how much the efficiency of the technology is improved, (2) how much of the less efficient technology is directly and indirectly replaced by the new technology, and (3) how much product is needed in the envisioned future. The difficulty in c-LCA is that (2) and (3) are uncertain from various socioeconomic reasons that are often difficult to predict. By organizing the results from product life cycle assessments in

a systematic way, the proposed methodology allows exhibiting the range of consequential changes in environmental impact associated with a technology innovation, taking into account those uncertainties on a plain coordinated by the amount of product needed in the future and environmental impact on the horizontal and vertical axes, respectively.

Results Part 1 describes the methodological framework in detail, whereas Part 2 elaborates on the applications of the methodology. By taking transportation technologies assuming various energy sources in Taiwan, the choices of technologies and the evaluation of technology improvements serve as the case studies to demonstrate the application of the methodological framework.

Conclusions By using the proposed method to organize the assumptions in c-LCA, discussions on different choices of technologies are made more systematic. In this way, stakeholders can focus on visions of future society, which lead to different choices of technologies.

Keywords Consequential LCA · Hydrogen society · Hydrogen technologies · Renewable energy · Transportation

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I.-C. Chen · Y. Fukushima (✉)
Department of Environmental Engineering and Sustainable
Environment Research Center, National Cheng Kung University,
No. 1 University Rd.,
Tainan City 701, Taiwan
e-mail: fuku@mail.ncku.edu.tw

I.-C. Chen · Y. Kikuchi · M. Hirao
Department of Chemical System Engineering,
The University of Tokyo,
7-3-1, Hongo,
Bunkyo-ku, Tokyo 113-8656, Japan

Nomenclature

Notations

c-LCA	Consequential life cycle assessment
P curve	Production curve
U curve	Utilization curve
I curve	Impact curve
GHG	Greenhouse gas

Symbols

P_{\min}	Minimum environmental impact induced from production process
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P_{\max}	Maximum environmental impact induced from production process
U_{\min}	Minimum emission reduction from utilization process
U_{\max}	Maximum emission reduction from utilization process
I_{\min}	Minimum environmental impact of applying composite technology
I_{\max}	Maximum environmental impact of applying composite technology
E_{PV}	PV power generation (in kilowatt hours per year)
i	Cities, counties
P_i	Power production per square meter in a year in city or county i (P_i is related to solar irradiation at each location)
A_i	Residential building roof area in city or county i
E_{CO_2}	Total CO ₂ emission (kilograms CO ₂ e)
N_i	Number of vehicles i
D_i	Average travel distance of vehicle i (in kilometers)
M_i	Average fuel consumption rate of vehicle i (kilometers per liter of fuel)
$EF_{CO_2, i}$	CO ₂ emission factor for fuel used in vehicle i (kilograms CO ₂ e per liter fuel)
i	Passenger car motorcycle

1 Introduction

The graphical representation for consequential life cycle assessment is proposed in Section 1 of this paper, which described the methodological framework. In Section 2, two case studies on the choice of technologies and evaluation of technology improvement are presented and discussed, which demonstrate the graphical method according to the methodology described in the following sections. Both of the two case studies discuss the innovation of hydrogen technology in a “hydrogen society” in Taiwan.

Energy security has always been a concern because of its high dependence on imported source of energy, e.g., 99.37% imported in 2009, among which, 13.16% used in the transportation sector (Bureau of Energy 2009). Moreover, pollutants from the transportation sector are causing serious environmental problems owing to the high population density, e.g., 639 people/km² in 2009 (Department of Household Registration 2010), and the high utilization rate of motor vehicles when people commute.

The use of hydrogen as an alternative energy carrier has been receiving attention for a number of reasons. Hydrogen is cleaner than fossil fuels because almost zero pollutants are emitted during the energy conversion. This characteristic can improve environmental quality because the

sources of pollutants can be centralized during the production of hydrogen rather than be distributed to locations where people visit or pass by with their vehicles. Moreover, hydrogen can facilitate the active use of unused and renewable energy sources because pathways to generate those into hydrogen are developed actively. Researches show the potential of hydrogen derived from biomass (e.g., agriculture and forest waste, kitchen waste, etc.), wind, and solar energy via thermal chemical, photochemical, or biological processes (Turner et al. 2007). In this way, the hydrogen society could promote independence from fossil fuels. This benefit is critical in many countries including Taiwan which relies heavily on imported fossil fuels. An important characteristic of renewable energy is its versatility, i.e., it is found everywhere in various forms, such as wind, solar irradiation, and biomass. Therefore, an energy system that is more geographically distributed can be designed, which has the advantages of a disaster-tolerant energy supply and the reduction of loss in energy transportation. To bring all those benefits into reality, research efforts have been invested into hydrogen-related technologies.

For Taiwan, hydrogen-based transportation systems based on renewable energy can be a particularly attractive solution to the aforementioned challenges. At the same time, Taiwan, as an island, realizes the importance of mitigating global warming and striving to reduce greenhouse gas (GHG) emission, although it is not a member party of United Nations Framework Convention on Climate Change.

There is a wide and growing literature exploring different possible pathways to a hydrogen-based future. Life cycle assessments (LCAs) of individual hydrogen technologies are found: several studies focus on hydrogen fuel production processes (Tugnoli et al. 2008; Koroneos et al. 2004) and hydrogen-utilizing applications (Granovskii et al. 2006), but none of them addresses the entire composite of technologies that should exist in an envisioned hydrogen society. However, a “hydrogen society” comprises multiple hydrogen technologies that interact with each other. Hydrogen production technologies compete over the limited demand for hydrogen and over limited resources for hydrogen production, while utilization technologies compete over a limited supply of hydrogen, which equals to the limited demand for energy generated from hydrogen. The interrelations among hydrogen production and utilization technologies are often less considered and absent in the current literature. Therefore, the composite assessment of hydrogen technologies is taken as case studies to demonstrate the graphical methodology that we proposed. The changes of environmental consequences by a technology innovation will be demonstrated, considering the changes of demand and the resulting possible environmental consequences of deployment.

2 Case studies applied to graphical representation for c-LCA

As stated in Section 1, the novel graphical method for consequential life cycle assessment (c-LCA) is designed for assessing technology and visualizing the environmental consequences. Four stages are included in the methodological framework described in Section 1, which are as follows: (1) define a technology domain, (2) calculate life cycle stages of the selected domain technology, (3) generate a graphical representation, and (4) interpret the results and provide feedback information.

2.1 Step 1: define a technology domain

The technology domain is selected as hydrogen technologies for Taiwan. There are two subdomains included: (1) production subdomain—renewable energy to hydrogen—and (2) utilization subdomain—hydrogen-fueled vehicles in the transportation sector. Two case studies (S1 and S2) on the choice of technologies and evaluation of technology improvement are conducted, as summarized in Table 1. Technologies of renewable energy to hydrogen include: water electrolysis by wind and solar energy and biohydrogen production (dark fermentation and two-stage process) using local sugarcane as feedstock; utilization technologies are trucks, passenger cars, and motorcycles used in Taiwanese transportation systems.

GHG emission was focused on as the environmental impact. The selected technologies in the two case studies are almost the same, whereas the biological hydrogen production technologies are different. The objective of this comparative evaluation was to realize how technology improvement can contribute to environmental impact reduction in a systematic point of view.

2.2 Step 2: calculate associated the environmental impacts of selected domain technology

2.2.1 Cradle-to-gate LCA in production subdomain

The cradle-to-gate LCA is conducted to calculate the technologies in the production subdomain: (a) water electrolysis by wind energy, (b) water electrolysis by solar energy, and (c) biohydrogen production using local sugarcane as feedstock.

The individual environmental impact associated with the production of a unit amount of feedstock should be determined together with the resources available for production.

(a) Wind energy + water electrolysis

Hydrogen production from wind is analyzed assuming electrolytic hydrogen production. A preceding research on the fundamental wind atlases and development potential map of wind energy in Taiwan (ITRI and NCU 2002) is applied in this study, which concludes that the potential installed capacity is approx. 28 GW in total. To obtain the capacity factors of the wind turbines, first, the wind speed simulations were performed by applying the 5-year actual wind speed data acquired from the Central Weather Bureau of Taiwan. Among large number of studies, the Weibull probability density function (PDF) is widely adopted to model the wind speed frequency curve (Patel 2006). By fitting time series data obtained from measurement, parameters in Weibull PDF can be derived. In this study, the Weibull PDF shown below is applied to simulate wind speed to respective locations:

$f(V) = \frac{k}{c} \left(\frac{V}{c}\right)^{k-1} e^{-\left(\frac{V}{c}\right)^k}$, where k is the shape parameter, c is the scale parameter, and v is the wind speed. The parameter k determines the shape of the distribution curve, $k=2$ is a typical pattern found at most sites, and parameter c represents the wind speed range. For the greater value of c , the distribution curve shifts right to a higher wind speed; that is, a higher c represents the greater number of days that have high winds. One of the simulated results is shown in Fig. 1.

Once the time course of the wind speed is simulated, power generation is calculated by applying a wind turbine characteristic curve (Chang et al. 2003) which describes the power output for various wind speeds. A turbine is operated between cut-in speed V_1 and V_O . $P(V)$ is the actual power output and P_R is the constant output at a range of rated speed V_R and cutoff speed V_O ,

$$P(V) = \begin{cases} 0 & , V < V_1 = 3(\text{m/s}) \\ (a_1 V^3 + a_2 V^2 + a_3 V + a_4) \cdot P_R & , V_1 \leq V < V_R = 15(\text{m/s}) \\ P_R & , V_R \leq V < V_O = 25(\text{m/s}) \\ 0 & , V \geq V_O \end{cases}$$

Using regression analysis, the values for all the parameters were obtained as follows: $a_1 = -0.001$, $a_2 =$

Table 1 Selected domain technologies for two case studies

	Production technology	Utilization technology
S1	Wind energy + electrolysis; solar energy + electrolysis; biomass (sugarcane) + dark fermentation	Transportation (trucks, passenger cars, motorcycles)
S2	Wind energy + electrolysis; solar energy + electrolysis; biomass (sugarcane) + two-stage process	Transportation (trucks, passenger cars, motorcycles)

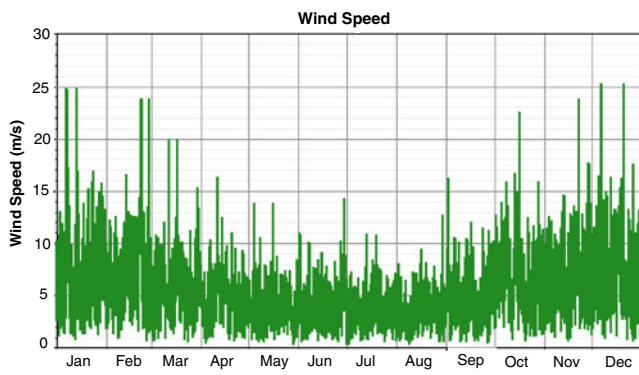


Fig. 1 Simulation of wind speed distribution over 1 year

0.030, $a_3=-0.176$, $a_4=0.292$, and $P_R=1,026$ kW. Then, by applying simulated hourly wind speed at the respective wind turbine sites throughout a year into the function obtained, namely, $P(V)=0$ when $V \leq 3$ m/s and $V \geq 25$ m/s, $P(V)=1,026 \times (-0.001 V^3 + 0.030 V^2 - 0.176 V + 0.292)$ when $3 \leq V < 15$ m/s, and $P(V)=1,026$ when $15 \leq V < 25$ m/s, respective power generation was obtained. Then, by applying a simulated hourly wind speed at the respective wind turbine sites throughout a given year, respective power generations are obtained. Commercialized process data (53.4 kWh/kg H₂; Ivy 2004) are applied to the obtained power production from wind power generators to calculate the annual electrolytic hydrogen production.

The environmental impact induced by wind power-derived hydrogen is calculated by life cycle assessment considering cradle-to-gate of the produced hydrogen. Manufacturing, foundation construction, operation, and disposal of wind turbine, as well as the energy consumption in the hydrogen production phase, were considered (Spath and Mann 2004; Lee and Tzeng 2008).

(b) Solar energy + water electrolysis

Hydrogen production from solar irradiation is estimated assuming the installation of photovoltaic (PV) modules on the roof of residential buildings (A_i) to generate electricity (Chang 2008) and connected to an

electrolytic process to produce hydrogen. Power production from solar energy depends on solar irradiation at each location (P_i). Simulation of solar irradiation by considering localized data (longitude, latitude, height, and temperature) is carried out by applying software called “PVsyst.” Solar power generation is estimated as shown in the following equation:

$$E_{PV} = \sum_i (P_i \times A_i).$$

The environmental impact of solar-derived hydrogen is calculated from the life cycle inventory data of the PV module production provided in the literature (Alsema and Mariska 2006) and then combined with the electrolysis process (Ivy 2004).

(c) Biohydrogen production using sugarcane

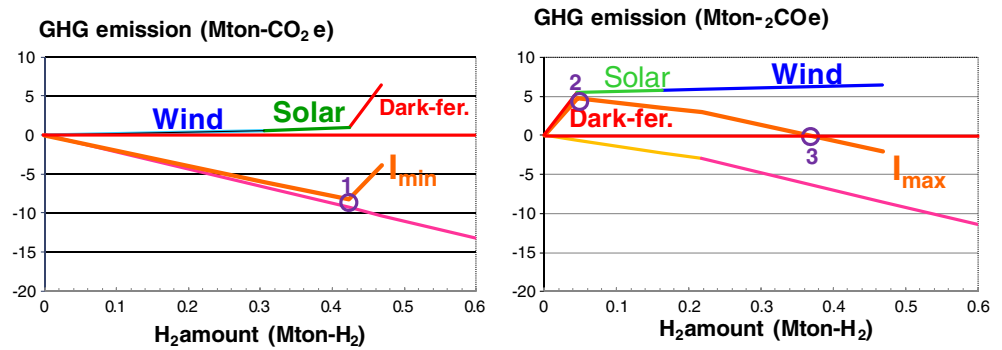
In this study, sugarcane is chosen as a feedstock to generate hydrogen. Two different production processes, i.e., dark fermentation and two-stage process, are evaluated (Manish and Banerjee 2008) using the same amount of sugarcane as feedstock.

A cradle-to-gate LCA is conducted for hydrogen produced from sugarcane (Fukushima and Chen 2009) to derive the environmental impact associated with the production of a unit amount of hydrogen. The processes included in the system boundary were sugarcane production, milling, and the hydrogen production processes and their background processes. GHG emission from electricity is calculated by the emission factor (0.637 kg CO₂e/kWh) provided by the Taiwan Power Company (Taipower 2008). However, the emission factor only considers the emission from fuel combustion for power generation. Power plant construction and operation and the maintenance of facilities should also be taken into account. Therefore, a modification based on a Tokyo Electric Power Company Group’s study (TEPCO 2009) is made. The emission inventory including cradle-to-gate of power in Taiwan is calculated as 0.715 kg CO₂e/kWh. To calculate this value, the Taiwanese power structure is taken into account (Fukushima and Kuo 2008).

Table 2 Life cycle inventory results of subdomain technologies (production and utilization)

	Process	GHG emission (<i>a</i>) (kg CO ₂ e/kg H ₂)	Capacity (kton) (<i>b</i>)	Total GHG emission (<i>a</i>) × (<i>b</i>) (kton CO ₂ e)
Production	Wind	2.02	306	6.18 × 10 ²
	Solar	3.20	117	3.74 × 10 ²
	Biomass (dark fermentation)	119.45	45	5.43 × 10 ³
	Biomass (two-stage process)	1.22	137	1.67 × 10 ²
Utilization	Diesel-fueled vehicles	-13.73	395	-5.42 × 10 ³
	Gasoline-fueled vehicles	-21.99	1,221	-2.69 × 10 ⁴

Fig. 2 Minimum (*left*) and maximum (*right*) environmental impact patterns of S1



2.2.2 Gate-to-grave LCA in utilization subdomain

The demand for hydrogen in the transportation sector is calculated by estimating the average commute distance in a year (in kilometers per year) of each type of vehicle (i.e., trucks, passenger cars, and motorcycles) and then multiplying with the fuel consumption rate (in kilograms of fuel per kilometer) to convert into fuel consumption (Ministry of Transportation and Communications 2009; ITRI 2005). GHG emission in the transportation sector is calculated based on the Intergovernmental Panel on Climate Change (IPCC) guideline using the following equation (IPCC 2007):

$$E_{CO_2} = \sum_i E_{CO_2,i} = \sum_i \left(\frac{N_i \times D_i}{M_i} \times EF_{CO_2} \right).$$

Therefore, if the transportation sector powered by fossil fuel can be replaced by hydrogen-powered vehicles, the environmental impact of fuel usage, which includes fuel extraction and combustion, can be reduced. The calculation stands on assuming trucks are fueled by diesel, while passenger cars and motorcycles are by gasoline. The environmental impact reduction potential with the replacement of fossil fuels was obtained using the equation above. In this case study, the displacement in hydrogen utilization technology is limited to the negative environmental impact because only fuel replacement is considered.

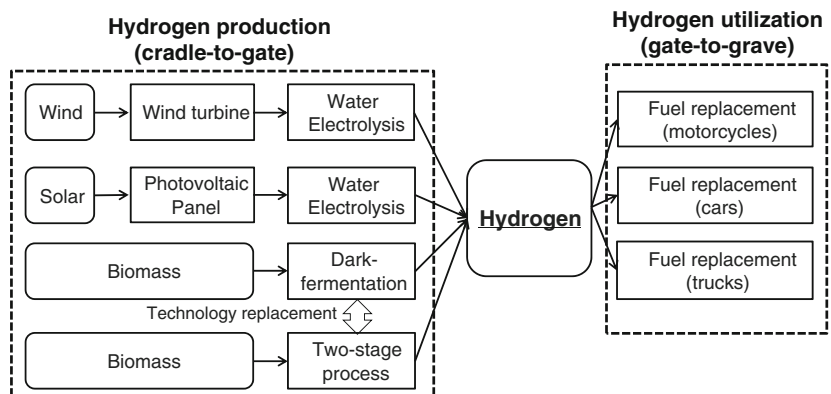
Each LCA and LCI result of the selected technologies is calculated and summarized in Table 2. In production technologies, the highest environmental impact induced by the production process is by dark fermentation, whereas the lowest environmental impact is by the two-stage process. In utilization technologies, diesel-fueled vehicles have lower fossil fuel combustions considering the unit traveling distance.

2.3 Step 3: generate a graphical representation

The results from Section 2.2 summarized in Table 2 are used to generate graphical representation. Data presented in the production and utilization subdomains are used to construct *P* and *U* curves, respectively. Then, the two curves are combined to synthesize the *I* curve, which shows the net environmental impacts over the extent of the technology domain. Figure 2 shows the minimum and maximum environmental impact patterns of S1. The introduction orders of minimum environmental impact pattern (*I_{min}*) are wind, solar, and dark fermentation in production technologies (*P_{min}*) and gasoline-fueled and diesel-fueled vehicles in utilization technologies (*U_{max}*). The maximum pattern (*I_{max}*, *P_{max}*, and *U_{min}*) is that all the technologies are introduced in opposite orders.

The three indicators for S1 are shown in Fig. 2 as well. Point 1 represents *maximum emission reduction*, which has a potential of 8.31 Mton CO₂e when 0.42 Mton H₂ is

Fig. 3 Scope of assessed hydrogen technologies in the case studies. Here, the cradle-to-gate of hydrogen production technologies (example, wind turbine manufacturing and installation) are considered; while in utilization domain, only fuel replacement is considered



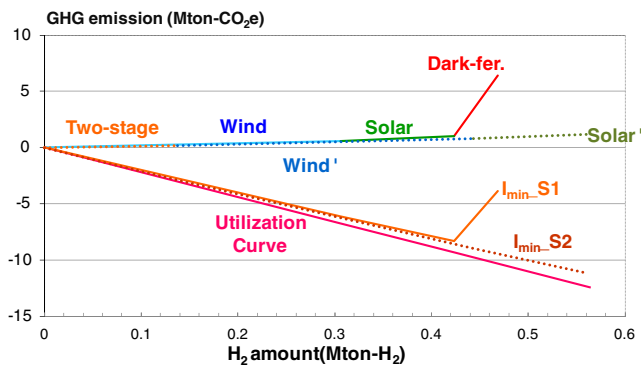


Fig. 4 Comparison of S1 (solid lines) and S2 (dotted lines) with minimum environmental impact pattern

utilized. “Maximum environmental impact” shown as point 2 is 4.81 Mton CO₂e, indicating that the largest emission might be generated by utilizing the domain technologies; “emission neutralization” is achieved when 0.36 Mton H₂ is utilized, shown as point 3. A similar procedure can be applied to S2.

2.4 Step 4: interpret results and provide feedback information

Figure 3 summarizes the technologies included in the assessment. Figure 4 shows the comparison between S1 and S2 based on the minimum environmental impact pattern. The results of S1 are presented as solid lines; the dotted lines are for S2. As stated in Table 2, the two-stage process has the lowest environmental impacts among all hydrogen production subdomain technologies. Therefore, the orders of introducing production subdomain technologies in S2 are changed from that of S1. Figure 4 also demonstrates the interactions among hydrogen production subdomain technologies. In the case of S2, biohydrogen production process becomes the most preferential technology, which makes sugarcane biomass earlier utilized than wind and solar resources. The yield of hydrogen production is enhanced and the impact curves are changed ($I_{min_S1} \rightarrow I_{min_S2}$).

Figure 5 shows the comparison result of indicators between S1 and S2. Three indicators—maximum emission reduction (0.42, -8.31), maximum environmental impact

Fig. 5 Comparison of indicators between S1 (left) and S2 (right)

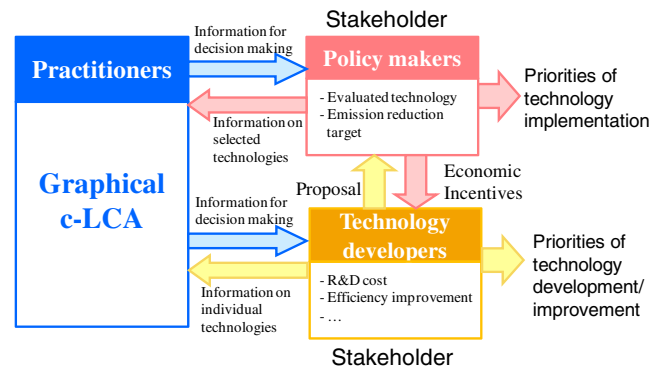
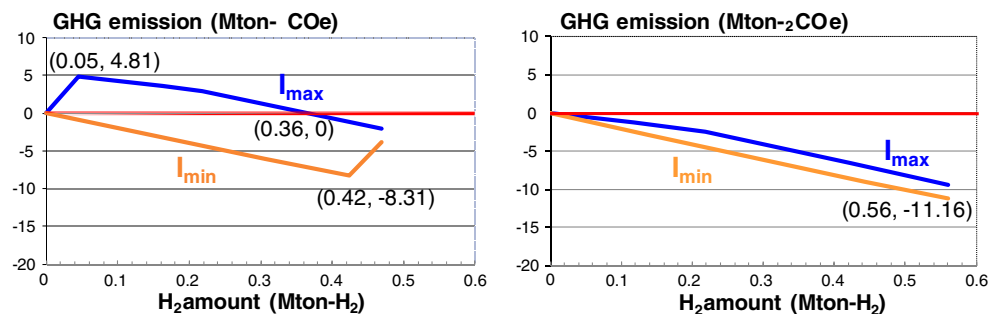


Fig. 6 Information flows and characteristics/interaction among roles

(0.05, 4.81), and emission neutralization (0.36, 0)—are discussed in S1; S2 only shows one indicator “maximum emission reduction” located in (0.56, -11.16), which indicates that 11.16 Mton CO₂e emission can be reduced when 0.56 Mton H₂ is utilized. The results illustrate that the introduction of the two-stage process will always bring environmental impact reduction because the environmental impact is negative at every point on the I_{max} and I_{min} curves. The results of the comparison on S1 and S2 indicate that the contribution of environmental impact reduction by the improved technology (i.e., two-stage process) is larger for two reasons: (1) the hydrogen yield is increased and (2) the emission will be reduced because the values of net environmental impact are always negative regardless of the actual choices of technology in the society determined by, for example, market mechanisms.

Depending on the consequences of choice made in the society, the environmental impacts in the future under S1 and S2 can be anywhere in the range surrounded by the respective I_{min} and I_{max} curves. Even though S2 seems to have a better opportunity to end up with a lower environmental impact, it is possible that S1 actually realizes a lower impact. However, as all the indicators show that S2 has a better collection of technologies, and as S2 is a no-regret situation in which a reduction in environmental impact is assured, while in the case of S1 there is a possibility to have an increase in environmental impact, S2 seems to be the better choice. Likewise, the decision maker will be able to take

uncertainties into consideration and reflect more information in their decisions, for example on whether investment should be made to implement the two-stage hydrogen fermentation process.

3 Discussion

Figure 6 shows a schematic of information flows among roles (practitioner and stakeholders) in the evaluated system. For example, when a new energy policy is proposed, policy makers may provide information on candidate technologies to the practitioner conducting the analysis. After the analyses, information will be provided again to policy makers to generate more a strategic policy. On the other hand, information flow between stakeholders also exists. For example, an environment-friendly technology can be proposed by a technology developer to apply for subsidies (or investment) from the government. With the support of the practitioner of the proposed methodology, technology developers can provide policy makers with data on the technology together with analyses on the usefulness of the technology in a more policy-relevant format, considering other competing technologies. The information provided to technology developers also contributes in prioritizing technology development tasks, for example among the improvement of hydrogen yield (extend respective segment of P curve in a horizontal direction) and the reduction of energy consumption in hydrogen production (reduction in the gradient of the respective segment of the P curve).

4 Conclusions

The presented case studies demonstrate the use of the methodology and show possibility of feedback on target efficiencies and consequential environmental benefits to the researchers developing the technologies being assessed. Three indicators are defined in the use of the graphical representation method: maximum environmental impact, emission neutralization, and maximum emission reduction. The result of graphical representation can clearly convey information on the environmental consequence of production and utilization technologies, the potential of hydrogen production and demand, and the resulting possible environmental consequences of the deployment of the given technologies. These provide information on the relationship between feedstock utilization and associated environmental impact, and it can be helpful for allocating resource effectively.

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References

- Alsema EA, Mariska JWS (2006) Environmental impacts of crystalline silicon photovoltaic module production. 13th CIRP International Conference on Life Cycle Engineering, Leuven
- Bureau of Energy, Ministry of Economic Affairs, Taiwan (2010) Available from: <<http://www.moeaboe.gov.tw/>> (in Chinese). Accessed 19 Dec 2010
- Chang CH (2008) Design platform for stationary PV systems in Taiwanese residential area. Bachelor thesis, National Cheng Kung University
- Chang TJ, Wu YT, Hsu HY, Chu CR, Liao CM (2003) Assessment of wind characteristics and wind turbine characteristics in Taiwan. *Renew Energ* 28:851–871
- Department of Household Registration, M.O.I, Taiwan (2010) Available from: <<http://www.ris.gov.tw/>> (in Chinese). Accessed 19 Dec 2010
- TEPCO (Tokyo Electric Power Company) (2009) Sustainability Report 2008, p 38. <http://www.tepco.co.jp/en/challenge/environ/report-e.html>. Accessed 1 Dec 2009
- Fukushima Y, Chen SP (2009) A decision support tool for modifications in crop cultivation method based on life cycle assessment: a case study on greenhouse gas emission reduction in Taiwanese sugarcane cultivation. *Int J Life Cycle Assess* 14:639–655
- Fukushima Y, Kuo YM (2008) Evaluation of GHG emission reduction potentials of PV system considering power mix shifts. *J Energy Eng—ASCE* 134(2):58–62
- Granovskii M, Dincer I, Marc AR (2006) Life cycle assessment of hydrogen fuel cell and gasoline vehicles. *Int J Hydrogen Energy* 31:337–352
- Ivy J (2004) Summary of electrolytic hydrogen production. Milestone Completion Report of National Renewable Energy Laboratory
- Koroneos C, Dompros A, Roubas G, Moussiopoulos N (2004) Life cycle assessment of hydrogen fuel production processes. *Int J Hydrogen Energy* 29:1443–1450
- Lee YM, Tzeng YE (2008) Development and life-cycle inventory analysis of wind energy in Taiwan. *J Energy Eng-ASCE* 37:53–97
- Manish S, Banerjee R (2008) Comparison of biohydrogen production process. *Int J Hydrogen Energy* 33:279–286
- Ministry of Transportation and Communications, ROC (2009). <http://www.motc.gov.tw/> (in Chinese). Accessed 30 Nov 2009
- Patel MR (2006) Wind and solar power system: design, analysis, and operation. Taylor & Francis, UK
- Spath PL, Mann MK (2004) Life cycle assessment of renewable hydrogen production via wind/electrolysis. Milestone Completion Report of National Renewable Energy Laboratory
- Taipower (2008) <<http://www.taipower.com.tw/>> (in Chinese). Accessed 25 Jun 2008
- ITRI (Industrial Technology Research Institute) (2005) Mechanical Engineering Industry Report. The average annual traveling mileage analysis in Taiwan (in Chinese)
- ITRI (Industrial Technology Research Institute) and NCU (National Central University) (2002) Assessment of wind power development potential in Taiwan (in Chinese)
- Tugnoli A, Landucci G, Cozzani V (2008) Sustainability assessment of hydrogen production by steam reforming. *Int J Hydrogen Energy* 33:4345–4357
- Turner J, Sverdrup G, Mann MK, Maness P-C, Kroposki B, Ghirardi M, Evans RJ, Blake D (2007) Renewable hydrogen production. *Int J Energy Res* 32:379–407
- Working Group I, IPCC (2007) The physical science basis. IPCC fourth assessment report: climate change 2007. Intergovernmental Panel on Climate Change (IPCC). Accessed 1 Dec 2009