A novel graphical method in consequential life cycle assessment for technological policy making

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Abstract To establish a future vision of sustainable society using innovative technologies, the expected environmental emission reduction should be assessed from life cycle perspectives for effective technological policy making. However, a systematic method to interpret the consequences of technology implementation based on assumptions on interrelations among technologies is still absent. In this study, we proposed a novel graphical representation method of consequential life cycle assessment (c-LCA), which visualizes the environmental consequences of technology implementation. A methodological framework for developing is presented, which uses case studies discussing scenarios of implementing various renewable energy sources and technologies into Taiwanese society. The visualized information makes it possible to feedback to early stage of technology design or regenerates a more strategic policy.

1 Introduction

There is a growing concern toward achieving sustainable development in modern society, leading to innovation of various environmentally friendly technologies. At the same time, a growing number of efforts have been made to track the roadmap via various emerging technologies, explicity or implicity, and there is a need to make assumptions on how the evaluated technology affects other technologies. For example, market mechanisms and cost projections can help simulate some of the technology interactions by assuming that market penetration occurs according to the cost minimization principle. Power generation technologies such as solar cells [1] and fuel cells [2] are evaluated by this approach. In these studies, technology innovations are interpreted into cost reduction, which then drive the market penetration.

For effective technological policy making, expected reductions in the environmental interventions induced by these technologies and the interrelations among technologies should be assessed from life cycle perspectives. Because many of the emerging technologies are interrelated with other existing and emerging technologies, a technology could replace another technology, or conversely be complemented by some other technology. Hertwich [3] has pointed out that a change in behavior (ex. technical change) can induce non linear changes in the achieved environmental impact reduction. It is highlighted that accompanying benefits and negative side effects of technical change should not be neglected. Consequential life cycle assessment (c-LCA) is the approach applicable, however, a system method to interpret the consequences of technology implementation based on assumptions on interrelations among technologies is still absent. Moreover, complicated procedural and results in c-LCA makes it difficult for decision makers to apply. Therefore, there is clearly a need for a methodological framework.

Here, we propose a novel graphical representation of c-LCA for technological policy making, which visualizes the environmental consequences. It allows analyses of the consequences of the implementation and/or replacement of various technologies in a systemic way.

2 Methodology

This graphical c-LCA method designed for assessing technology is summarized in Fig. 1. It presents the major building blocks of the methodology, which has four stages being included: (1) define a technology domain, (2) calculate life cycle stages of selected domain technology, (3) generate a graphical representation, and (4) interpret the results and provide feedback information.

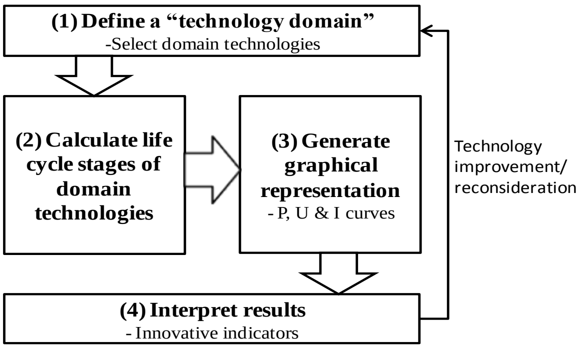

Fig. 1: Method of developing graphical c-LCA

2.1 Define a technology domain

First, the evaluated technology domain should be defined. A process of production or utilization associated with the evaluated product is defined as a technology. Each technology is classified into either production or utilization technology. An initial collection of production and utilization technologies is set based on specific criteria and constraints. For example, "renewable hydrogen technologies" is assumed as the technology domain that produces and utilizes hydrogen via renewable energy sources. This is at the stage of "goal and scope definition" in the LCA framework.

2.2 Calculate life cycle stages of selected domain technology

Then, the environmental impacts of selected domain technologies are calculated according to their life cycle stages (i.e., production and utilization). A cradle-to-gate LCA is conducted for products produced via each production technology to derive the environmental impact associated with the production of a unit amount of feedstock. At the same time, resources available for production are evaluated. To obtain the information described above, life cycle inventory analysis (LCI) and life cycle impact assessment (LCIA) are implemented.

A gate-to-grave LCA is conducted for utilization via using various technologies. Such analyses derive environmental impact reduction induced by the utilization of a unit amount in the respective technologies. At the same time, demands for functions delivered via respective utilization technologies are evaluated. Similarly, LCI and LCIA are required.

2.3 Generate a graphical representation

Next, a graphical representation can be generated using the results obtained from section 2.2. Figure 2 illustrates how an individual life cycle result of a technology is assembled. Each segment in Fig. 2 represents a technology (P1…P4 and U1…U4).

Production (i.e. P1…P4) and utilization (i.e. U1…U4) segments represent different technologies. The vertical element of a segment is the environmental impact calculated from respective product LCA study, while the horizontal element depicts the availability of the technology. In the left part of Fig.2, the segments are put in order by their gradients (P1, ..., P4 and U1, .., U4) to construct the minimum environmental impact (Pmin) and maximum environmental impact reduction (Umax) curves, respectively. Minimum impact (Imin) curve is synthesized from Pmin and Umax curves. Similarly in right part of Fig. 2, the segments are connected into curves but in the reverse order (P4, …, P1 and U4, …, U1). The resulting maximum environmental impact (Pmax) and minimum environmental impact reduction (Umin) curves are used to synthesize maximum environmental impact (Imax) curve.

Theoretically, all of the environmental consequences of the combinations are located in the range encompassed by Imax and Imin curves.

2.4 Interpret the results and provide feedback information

The environmental effects among corresponding technologies are visualized and can provide information for strategic decision making. For example, different scenarios of technology implementation under various economical and social circumstances can be accessed via the graphical representation. Feedback such as technology reconsideration is obtained when the results need to be reexamined.

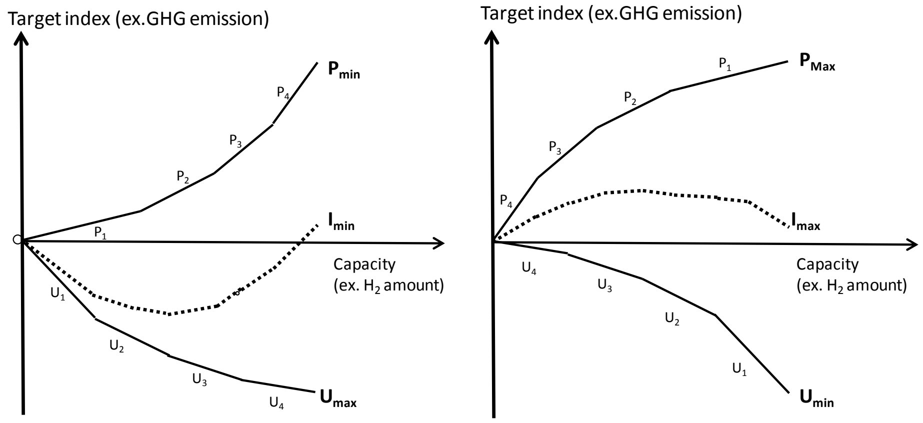

Fig.2: Graphical representation of c-LCA explained in the context of evaluated production/utilization technologies (left: minimum pattern; right: maximum pattern)

3 Case study

The applications of this proposed methodology are demonstrated by case studies discussing scenarios of implementing various renewable energy sources and technologies into Taiwanese society.

3.1 Technology domain: hydrogen-based technologies

The technology domain is selected as hydrogen-based technologies in Taiwan. Two subdomains included: (1) production subdomain: renewable energy to hydrogen, that is, water electrolysis by wind and solar energy, and biohydrogen production using local sugarcane as feedstock, and (2) utilization subdomain: hydrogen-fueled vehicles in transportation sector replace trucks, passenger cars and motorcycles used in Taiwanese transportation systems. Greenhouse gas (GHG) emission was focused on as the environmental impact.

3.2 Calculate each of the life cycle results of domain technologies and apply them to generate graphical representation

Hydrogen production capacity and GHG emission associated with utilization processes are estimated as shown in Tab. 1. Data such as availability of resource (wind condition [4], solar irradiation, installable area, biomass availability, etc.) and energy consumptions associated with hydrogen production [5-8], emissions from fossil fuel combustions [9], and demand of different kinds of vehicles [10] were used in this study to generate the LCA results of each domain technology.

Then, the results in Tab. 1 can be used to generate graphical representation. Fig. 3 shows the minimum and maximum

Tab. 1 Hydrogen production and utilization capacity and associated GHG emission

Process		GHG emission*	Capacity (kton)
Production	Wind	2.02	306
	Solar	3.20	117
	Biomass(dark-fermentation)	119.45	45
Utilization	Diesel-fueled vehicles	-13.73	395
	Gasoline-fueled vehicles	-21.99	1,221

Note: Units: *kg-CO_2eq./kg-H_2,.

environmental impact patterns. The introduction orders of minimum environmental impact pattern are wind, solar and dark fermentation in production technologies, and gasoline-fueled and diesel-fueled vehicles in utilization technologies. The maximum pattern is that all the technologies are introduced in opposite orders.

The three indicators are shown in Fig. 3 as well. Point 1 represents "*Maximum emission reduction*", which has a potential of 8.31 Mton-CO_2 when 0.42 Mton-H_2 is utilized. "*Maximum environmental impact*" shown as point 2 is 4.81 Mton-CO_2, indicating that the largest emission might be generated by utilizing the collected technologies, and "*Emission neutralization*" is achieved when 0.36 Mton-H_2 is utilized, shown as point 3.

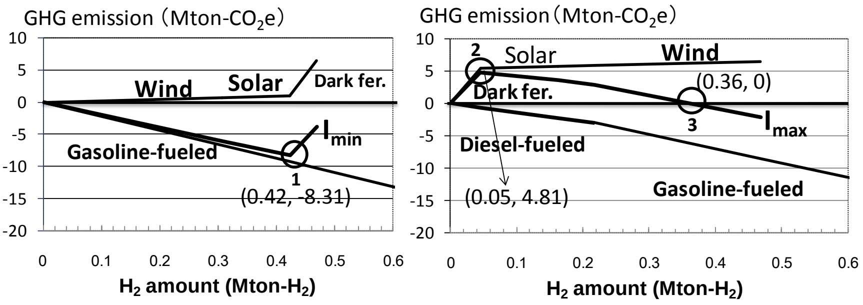

Fig. 3: Minimum (left) and maximum (right) environmental impacts patterns

3.3 Interpret the results of the case study

According to the graphical representation results shown in section 3.2, hydrogen production via renewable energy is insufficient to meet the demand in utilization. To solve this problem, there are various alternatives can be implemented. For example, the insufficient of hydrogen is filled up by natural gas (NG) steam reforming process, which releases 11.888 kg-CO2 when 1kg of hydrogen being produced, considering impacts from raw material extraction, construction, operation, and disposal. [11]. Fig. 4 shows the results of minimum pattern when NG derived hydrogen is implemented. According to the result, to implement fossil fuel derived (i.e., NG) hydrogen into society can increase environmental impact reduction to 17.74 Mton-CO2 (Fig. 5). Such procedure can be followed and help to regenerate a more strategic policy.

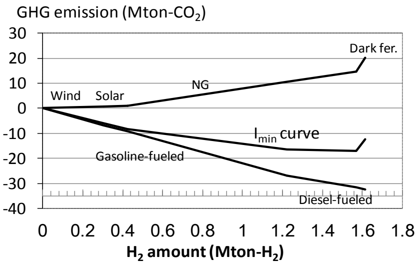

Fig. 4: Minimum pattern (NG derived hydrogen is implemented)

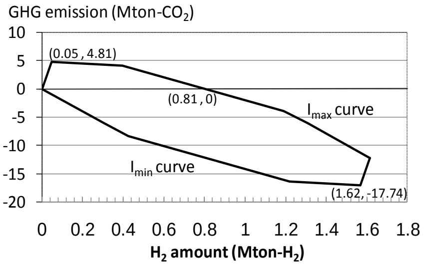

Fig. 5: Theoretical environmental impact region

4 Results and discussions

The presented case studies demonstrate the use of the methodology, and shows 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 c-LCA graphical representation: maximum environmental impact, emission neutralization and maximum emission reduction. These provide information on the relationship between feedstock utilization and associated environmental impact.

The proposed methodology visualizes the environmental effects among corresponding technologies. This is especially useful for assessing different scenarios of implementation of technologies under various economical and social circumstances. In this way, stakeholders (ex. technology developers and policy makers) can concentrate on discussions of visions of the future society that lead to different choice of technologies.

5 References

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