博士論文

Scenario Analysis using Graphical Representation for Developing Technology Introduction Strategies

（技術導入戦略立案のための可視化手法を用いたシナリオ分析）

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Abstract

For the last two decades, "Sustainable Development" has emerged as an important concern all over the world. While technology innovation is prompted and accelerated much faster in modern society, it is believed that appropriate management policies for emerging technologies play a significant role in the transition toward sustainable society.

To support strategic policy making, a framework for developing technology introduction strategies is proposed. In this framework, a visualized analysis scheme which can comprehensively assess a combination of multiple technologies was developed. This framework has advantages in (1) helping our understanding of performance and behavior of technology introduction scenario, (2) identifying the relationships and trade-offs among different evaluation indices, and (3) visualizing various technology introduction scenarios in which time frame is taken into account.

Two case studies on the design of energy systems were carried out: (1) a hydrogen-related technology in Taiwan, and (2) an electricity system in Japan. The applicability of the proposed framework was demonstrated. These case studies represent two distinct types of systems design: grassroots and retrofit designs, which require different tasks in the design process.

Finally, this developed framework is represented by an activity model using a standardized activity modeling method (IDEF0). By this activity model practical activities with information flows in executing the process of strategic decision making is hierarchically clarified. The collaboration relationships among three types of stakeholders, i.e., management, assessment, and development, involved in generating new technology strategies is described by the model with the information flows among three individual

activity models.

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CHAPTER 1 INTRODUCTION

1.1 Strategies for sustainable development

1.1.1 Technological innovation in the society

For the last two decades, “Sustainable Development” has emerged as an important concern all over the world. A wide range of nongovernmental and governmental organizations has embraced the sustainability concept as a new paradigm in development (Lélé, 1991; Hammond, 2000; Clift, 2006). Within the discussion, the most widely used definition of sustainable development is the one developed by the National World Commission on Environmental and Development: development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). In order to satisfy future needs, it is important to find effective methods to lower environmental load and reduce consumption of resources at present.

Due to the growing interest in achieving a sustainable society, faster innovation in technologies is needed in modern society. For example, electric, hybrid, and hydrogen vehicles are being developed and introduced into the market, aiming to reduce the dependence on fossil fuels and to ease the stress of global warming and thus human society is transforming the transport system into a more energetically sustainable one by implementing effective energy technologies (Johnson & Chertow, 2009; Williams et al., 2011; Williams et al., 2012). The development and deployment of advanced technologies have been, and will be continued in various fields. These innovations allow the delivery of much more efficient services. Especially in the energy area, energy supplies have been expanded through improved exploration and extraction techniques. Technology innovations have increased the efficiency of energy conversion and end-use, as well as the availability and quality of energy services. Moreover, the environmental impacts of energy extraction, energy conversion, and energy use have been reduced (Sagar & van der Zwaan, 2006). These technology innovations can be categorized into two types. One relates to traditional or fossil fuel-based energy sources, such as high-efficiency and low-emission coal-fired power generation technology. The other corresponds to alternative or renewable energy sources such as wind, solar, and biomass.

Innovation broadly refers to the use of new ideas to improve the current ways of satisfying some requirements. However, as our demands approach to the environmental capacity, the unsustainable aspects of many development practices have become apparent. Through technology innovation, new or improved technologies are developed and implemented in society, thus innovation is relevant to policy making. Policy has influence on the direction of technology innovation by encouraging or facilitating the adoption of new ideas and practices; however, policies can impede adoption of new technologies as well. It is believed that an appropriate policy making for management of emerging technologies can play a significant role in the transition to sustainable society, not only in regional (Rees, 1988;Kørnøv & Thissen, 2000) but also in national levels (Barker & Smith, 1995; Saritas, Taymaz, & Tumer, 2007; Yasunaga et al., 2009). These studies suggested that strategic management of technology innovation is necessary toward a sustainable future.

1.1.2 Strategic management of technology innovation

One of the important disciplines in the strategic management of technology innovation is technology assessment. Technology assessment (TA) is a well-established concept (Decker, Ladikas, & Eds., 2004; Garud & Ahlstrom, 1997; Uotila & Ahlqvist, 2008), and is an effective tool for contributing better technology governance and acceleration in a broad field. TA enables the evaluation of aggregated capacity of a technology and strategic technology planning. For instance, TA has considerable potential to enhance innovation in agriculture and to assist agricultural industries in becoming more efficient, more sustainable and more socially acceptable (Vanclay, Russell, & Kimber, 2013). Several alternative power generation technologies are also evaluated by TA framework to support development of "clean and green" energy. Application of TA to water resource management has been done by comparing different sanitation technologies, and could identify appropriate wastewater treatment options for various decision-making situations (Kalbar, Karmakar, & Asolekar, 2012). Those studies suggest that TA can help decision makers decide appropriate technologies.

Various stages can be distinguished in the "life" of a technology, from invention through innovation, commercialization, diffusion, and finally maturation (Klepper, 2011). Generally, technology that has been developed earlier or has attained lower cost compared to that of existing technologies can be introduced to the market. Once a technology is technically and economically ready, environmental assessment of such technology would be addressed. If such "stand-by" technology does not meet certain environmental requirements, additional improvement would be considered. However such assessment tends to be carried out at the final stage of technology development. Environmental considerations have gained less priority among various objectives such as economic feasibility, despite the fact that the technology has been developed for “environmental friendliness”.

As some researchers (Heinzle & Hungerbühler, 1997; Ruiz, 2000) have pointed out, there could be clear advantage if environmental technology assessment can be carried out in earlier stages of technology development, because of higher freedom of design provides chances of improvement. **Table 1-1** summarizes the characteristics of environmental technology assessment in different stages of technology development. As shown in the table, questions addressed in each stage could be quite different. In the earlier stages, questions could be directed to technologies that are required to build a final product and its lifecycle stages. The amount of information available for environmental technology assessment is less in the earlier stages, thus studies in this part of the table are few. However, as emphasized in the column of “Improvement chances”, there could be greater chance of improvement (e.g. environmental performance) if such environmental technology assessment could provide feed-back to the development of the emerging technologies by overcoming uncertainties and lack of information.

Table 1-1 Characteristics of environmental technology assessment in different stages of technology development

Technology development Stages	Typical questions addressed	Development flow	Improvement chances	Information available	Studies
Retrofit	"How can we reduce the environmental impacts associated with this product?"	**Mature**	**Small**	**Large**	**Numerous**
Market penetration (substance of existing product)	"Does this abatement technology actually reduce (or minimize) environmental impacts?"				
Product / Process Design	"Should we save energy, or save material?" "Which raw material should be used?" "Should we increase durability, or should we increase recyclability?"				
Research & Development	"If realized, does this technology have a good chance to reduce environmental impacts?" "What would be the actual bottom-line efficiency of this technology?" "Which of the many possible breakthroughs are more critical and urgent?"	**Early stage**	**Large**	**Small**	**Few**

Since the amount of available information increases as the technology is developed, more information can be incorporated into the decision making process. For example, when a production process for a certain material is investigated, choices in processes will be limited once the raw materials are fixed. However, as research and development (R&D) regarding such material matures, there will be a selection of promising raw materials, therefore, combinations of processes and raw materials can be explored, and the optimal combination of raw material and processes could be chosen. As a result, pre-assessment becomes crucial and urgent in modern society, because it can 1) provide researchers of environmentally friendly technologies at earlier stages with information on environmental impact, possible barriers, and bottom-lines of the technologies, and 2) allocate R&D resources in a strategic manner according to the importance of such technologies.

To assist appropriate implementation of sustainable technologies, comprehensive tools and approaches that play an essential role in strategic policy decision have been presented (Robèrt, 2000; Robèrt et al., 2002; MacDonald, 2005). By carrying out environmental assessment at the R&D stage, higher degrees of freedom with regards to changes in design of technology can be achieved. This has been highlighted in a previous study in which a stochastic methodology to deal with associated uncertainties (Hoffmann, 2001). Moreover, the perception that engineers have a responsibility not only to their employers or clients but also to society as a whole is gradually being accepted in recent years (Clift, 2006). The method of evaluating the effectiveness of different cleaner technologies and how engineers can contribute in the method have been illustrated (Clift, 2006). As seen above, planners and engineers are called to design solutions with a wider scope in project and product life cycles. Nowadays, even researchers in laboratories working on small parts of process systems are asked to team up and consider implications to technology development from system-wide studies of designs with different aspects (Fukushima et al., 2011).

In the case of multi-objective design, identifying major trade-offs and minimizing them through elimination of inferior alternatives have significant effects is recommended (Gibson, 2013). While there are numerous aspects in the assessment of technology, in regard to the environmental aspect, life cycle assessment (LCA) is considered as a useful tool for studying system-wide environmental impacts of respective technologies (Baumann & Tillmann, 2004). LCA is a methodology, which is used to analyze the environmental impacts associated with goods and services directly and indirectly within a product's life cycle. The concept of product "life cycle" can be understood intuitively by metaphor to human beings using the phrase "cradle to grave". That is, a product is evaluated throughout its "cradle to grave" from the extraction of raw materials, through production, use, recycling, and to the final disposal. There is an international standard for LCA that lists the following applications: identification of improvement possibilities, decision making, choice of environmental performance indicators and market claims (ISO 14040, 1997). The standardized methodology provides a useful guideline for quantifying the environmental impact induced from products and services.

LCA has been accepted as an environmental management tool to evaluate and compare different products, as well as for process selection, design and optimization. This method can help identify opportunities for reducing the impacts associated with wastes, emission and resource consumption. It also provides possibilities to compare the improvement of technologies, enabling strategic decision making in environmental and economic aspects (Rule, Worth, & Boyle, 2009; Zhang et al., 2010).

1.2 Research needs

Although the above-mentioned assessment tools have played significant roles in developing effective solutions for a sustainable society, there are still challenges remaining. Since a single product is no longer sufficient to cope with the dynamic market environment, more integration of products and services has been offered to the market. Economic, social, and technological changes make the system much more complicated than ever before. Furthermore, uncertainty that resulted from various socioeconomic reasons often makes trends of the future difficult to predict. Three main challenges are illustrated in the following paragraphs.

- **Challenges 1: Interactions between corresponding technologies are omitted**

During a complete analysis, the product and every stage of its life cycle are explicitly analyzed. When more than one product can deliver the same function, or more than one life cycle pathways are in the scope of the study, results of each combination of choices (often defined as scenarios) are presented. As claimed above, however, assessing a single product and service without considering the interactions between corresponding technologies belonging to the system boundary is usually insufficient.

Regarding to system boundary selection and inventory data compilation, two approaches are used, namely attributional life cycle assessment (a-LCA) and consequential life cycle assessment (c-LCA), respectively (Ekvall & Weidema, 2004 ;Ekvall & Andrae, 2006). Both a-LCA and c-LCA can be utilized to support decision-making. a-LCA highlights the environmental impacts associated with the product. As demonstrated in analyzing carbon and water footprint activities, a-LCA is useful for communication and identification of improvement opportunities of existing products. In addition to the direct consequences induced by decision-making, c-LCA aims to describe the indirectly induced consequences as well. By integrating economic models to incorporate market information, c-LCA is also able to describe marginal environmental consequences associated with a new action. As shown in the review by Earles & Halog (2011), c-LCA has emerged as a tool for capturing possible effects on policy-making and strategic environmental planning under physical, technological, economic or political constraints. For the purpose of change-oriented assessment for new-implemented technologies, c-LCA would be an appropriate approach to support strategic policy-making and to identify the environmental consequences regarding technical changes.

However, a general framework for modeling the interrelations between technologies is yet to be established. For the primary indirect effects, market mechanisms and cost projections can help simulate part of the technology interactions by assuming that market penetration occurs based on the cost minimization principle. Power generation technologies such as solar cells (Fukushima & Kuo, 2008), wind turbines (Kuo & Fukushima, 2009), and fuel cells (Fukushima, Shimada, Kraines, Hirao, & Koyama, 2004) have been evaluated by this approach. In these studies, technology innovations are defined as cost reduction, which drives market penetration under constrained resource, social/political setting, and projections of various key factors. These studies also assessed which existing technologies would be replaced by new technology and competition relationship between technologies from economic perspective is presented. As to the secondary indirect effects, Hertwich (2005) pointed out that a behavior change driven by technology introduction can induce nonlinear changes in the achieved environmental impact reduction, and that accompanying benefits and negative side effects of technical change should not be neglected. Several quantitative models also have been proposed, but none of them is comprehensive enough to cover all the secondary indirect effects. c-LCA has attracted attention recently due to its ability to describe both primary and secondary indirect effects; however, a standardized procedure is still under development (Earles and Halog, 2011).

- **Challenges 2: Numerous factors and trade-offs in technology management for achieving sustainable society**

Despite numerous worldwide actions calling for adaptation of more sustainable strategies, little has been done on a practical level. This can be explained by the complexity of the issues. Sustainable development that guide sustainable planning in different fields can be attributed to three dimensions: environmental, economic, and social system respectively (Al-Sharrah, Elkamel, & Almanssoor, 2010; Azapagic & Perdan, 2000). Usually these issues are not stand-alone, thus distinguishing partial sustainability does not equal to reaching whole sustainability. Moreover, trade-offs exist everywhere in the decision making process. Identifying and minimizing major trade-offs through intentionally elimination of bad alternatives have demonstrated significant effects (Gibson, 2013). As shown in **Figure 1-1,** quantitative assessment of technical systems during the “research and development” and “planning and structuring” phases is important for identifying and prioritizing overall contributions to sustainability (Assefa & Frostell, 2007).

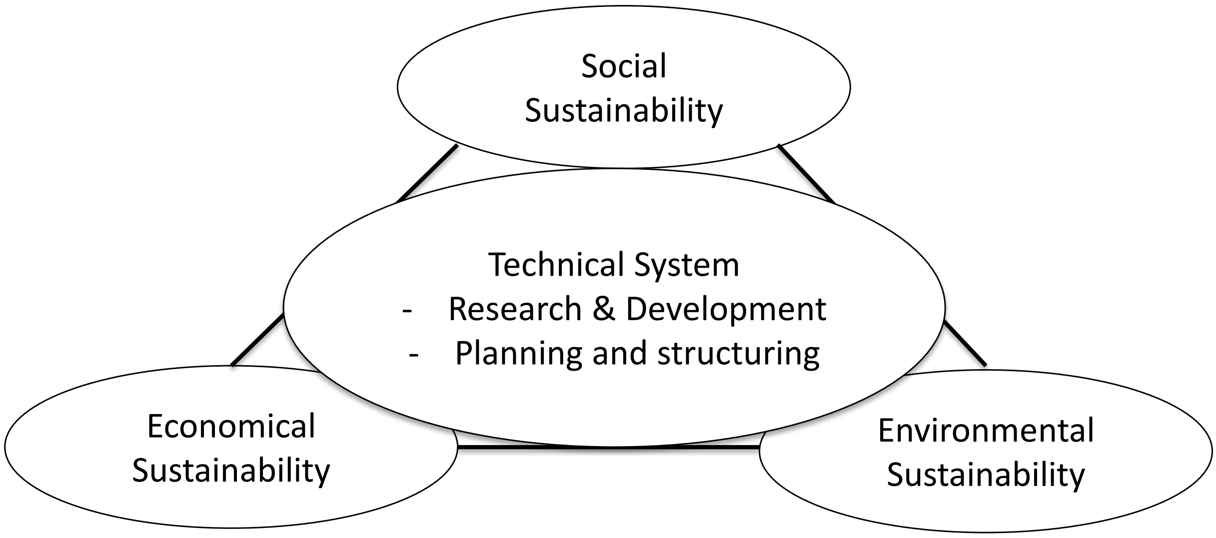


Figure 1-1 Three dimensions of sustainability functioning by technical system (adopted from Assefa & Frostell, 2007)

- **Challenges 3: Uncertainties for predicting future situation**

The future is full of complexity and uncertainty, which only enhances the difficulties for developing a sustainable future. Many types of uncertainties have been classified: data uncertainty, model uncertainty, completeness uncertainty, statistical variation, inherent randomness, systematic errors, parameter uncertainty, scenario uncertainty and so on (US-EPA, 1989; Morgan & Henrion, 1990; Bevington & Robinson, 1992; Huijbregts, 2001). These different types of uncertainty also form levels that relates to the role of the person experiencing the uncertainty (Huijbregts & Huijbregts, 2004). Scientists may feel uncertainty on the value of a certain parameter, while decision makers may feel uncertainty on the decision to be made. This kind of recognition difference may be of critical importance in terms of choice of methods to deal with uncertainty.

There are many approaches to deal with deal with uncertainties. For the decision makers, a systematic analysis approach should be offered to solve the uncertainty problems and response to better management in policy development. In this approach, a more transparent and operational framework for stakeholders is required to fill the gaps within decision-making for developing technology introduction strategies in the future. Furthermore, since the sustainable system at present is not assured to be sustainable in the future, time aspects should also be treated as a significant factor in technology introduction.

1.3 Thesis Statement

This thesis aims to present a practical framework for developing technology introduction strategies from comprehensive viewpoints including environmental, economic and with long-term perspectives. To attain this objective this dissertation focuses on development of a novel graphical representation method used to visualize consequences of technology introduction and support decision-making processes. Because complexity and uncertainty increase the difficulties in developing future policies, scenario analysis approach is used to systematically assess the consequences of technology implementation under various constraints. Case studies, in which two types of systems design are demonstrated, prove the applicability of the framework with the proposed graphical representation method.

The expected benefits from the proposed method and framework are as follows.

- Visualization of the theoretical range of environmental consequences when a set of technologies in the same domain is implemented. The visualization enables decision makers to cover and identify all potential consequences of technology combinations.

- Identification of detailed technology combination by visualizing trade-offs between different evaluation indices and operational optimum of each index. It helps decision makers to have a bird's-eye view in the scenario development.

- Clarification of required activities, information, tools and resources to support strategic policy making.

1.4 Thesis structure

The structure of this thesis and relationship among the chapters are presented in **Figure 1-2**. In **Chapter 1,** the current situation in sustainable development and challenges to achieve it are described. Based on the investigation of existing studies, the objective of this study is declared.

After a general introduction the principle of scenario generation and how scenario analysis is applied to the development of future decisions and research are reviewed in **Chapter 2**. The key factors for generating scenarios are summarized and categorized and they can serve as a framework for identifying external forces when generating future scenarios.

In **Chapter 3** a novel graphical representation method to support the systems design is described. The method visualizes the consequence of the implementation of target technologies and their corresponding technologies from different evaluating aspects, i.e. environmental and economic aspects within a certain time frame. By visualizing the trade-offs between different indices with detailed information of technology combinations, effects of technology introductions can be quantified at the early stage of system designs.

After the introduction of visualization method, two cases studies are demonstrated in **Chapter 4**. The graphical representation method proposed in **Chapter 3** is applied to grassroots and retrofit system designs. The value and applicability of the developed methodology is discussed.

Based on the method and case studies proposed and discussed from Chapters 2 to 4, a framework that considers the cooperation of different stakeholders in decision-making process is presented in **Chapter 5**. An activity modeling method, type-zero method of Integrated Definition Language (IDEF0), is used to incorporate management, assessment, and development under a hierarchical basis which can be utilized by different stakeholders. All required activities, information, tools and resources during the decision-making process are structured and clarified to support the strategic technology introduction.

Chapter 6 is the conclusion of this thesis. A summary of the strengths and limitations of the methodology is presented.

In **Chapter 7** other possible applications by utilizing the methodology is discussed, and some recommendations for future work are raised.

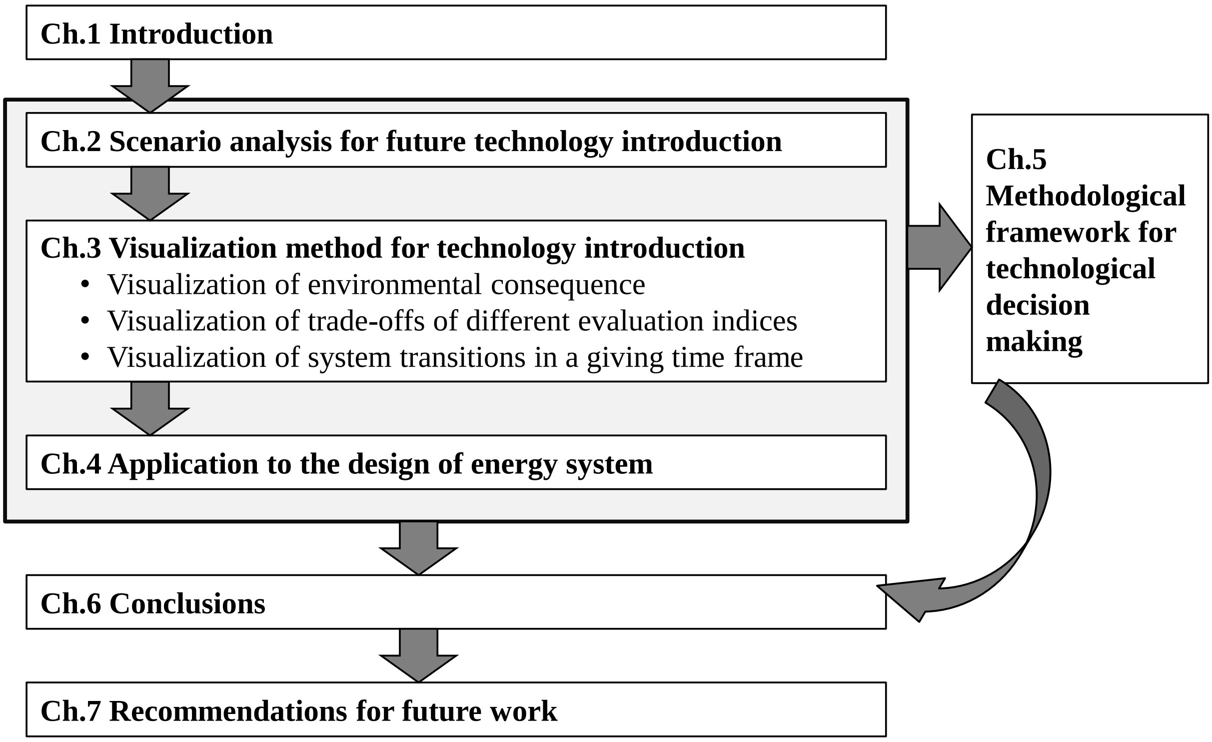


Figure 1-2 Thesis structure and the relationship between each chapter

CHAPTER 2 SCENARIO ANALYSIS FOR FUTURE TECHNOLOGY INTRODUCTION

2.1 Introduction

To develop strategies for future technology introduction numerous technology assessment aspects should be considered. For example, market mechanisms and cost-effective optimization methods, are often used for technology implementation planning when designing energy systems. During such decision planning the combination of technologies in a system is affected by not only economic, but also environmental, social and technological constraints and driving forces. In order to deal with such complicated situations in decision-making, “scenario analysis” is frequently used in this study to develop robust strategic plans by simplifying the impacts of potential consequences.

In this chapter, how scenario analysis is integrated with LCA studies and the principles of scenario generation are discussed first. The application of scenario analysis for future research is described in the following section.

2.2 Scenarios in life cycle assessment

Life cycle assessment (LCA) is a method that assesses environmental impacts at all the life stages of a product (i.e. started from raw material extraction, through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling). Nowadays, LCA is a well-accepted environmental management tool to systematically quantify environmental burdens and potential impacts over the entire life cycle of a product, process or activity. The typical LCA procedure and application are summarized in **Figure 2-1**. The framework of LCA includes the following steps:

- Goal and scope definition: The product and the purpose of the study are defined in this step. This is a key step to define the context of the study as well as how and whom the results are to be communicated. The system boundaries and types of environmental impacts being considered should be clearly defined here before being applied to the whole study.

- Life cycle inventory analysis (LCI): When constructing a quantitative flow model in this step, system boundaries should be defined according to the goal and scope. It is necessary to collect inventory data for all the activities (processes and transports) in the product system. This inventory data includes inputs and outputs of respective activities, such as raw materials and energy usage, yield of products, amount of solid waste, and emissions to the environment. Finally, the environmental interventions of the system in relation to the defined functional unit are calculated.

- Life cycle impact assessment (LCIA): this step aims at describing the environmental loads quantified in the inventory analysis. This objective is achieved by translating the environmental load from the inventory results into environmental impacts, such as themes (e.g. global warming, acidification, ozone depletion) and damages (e.g. effect on biodiversity, human health, etc.).

- Interpretation: in this step, results acquired from the LCI and LCIA are organized in the most appropriate form in order to deliver recommendations. This includes identification of significant issues (e.g. important environmental findings and critical methodological choices) and evaluations to establish confidence in the results via sensitivity and uncertainty analyses. Occasionally a project has to be terminated after interpretation, but in most cases the product system becomes better understood, thus elaborated analyses can be initiated by going back to the previous three steps.

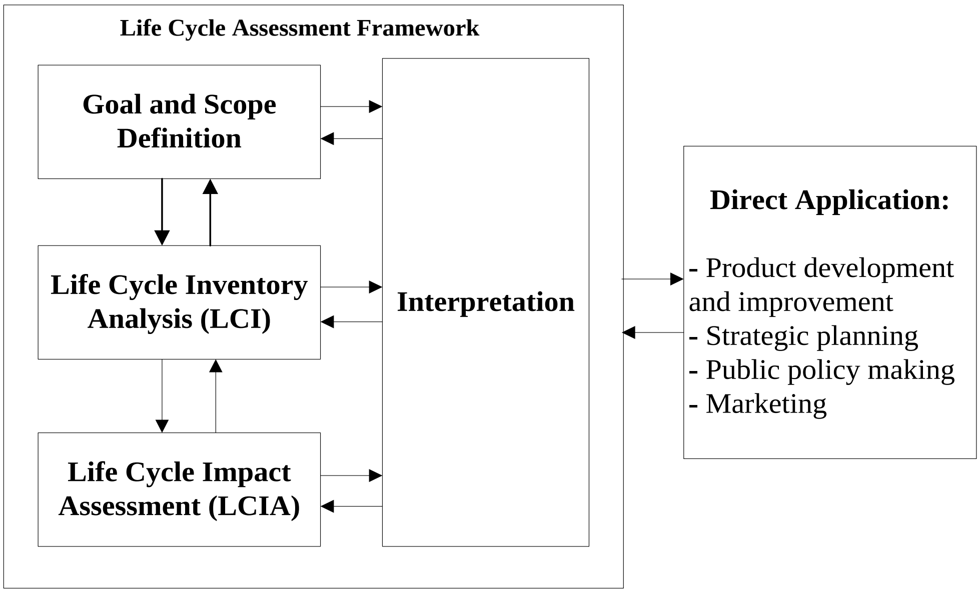


Figure 2-1 The LCA procedure and application

Although the LCA framework defined as ISO 14040 is broadly applied to calculating environmental impacts associated with a functional unit of product and service, system dynamics with “time frame” are less considered. Therefore, by predicting possible future situations, both explicit and implicit scenarios are important for the application of LCA (Martinot, Dienst, Weiliang, & Qimin, 2007; Spielmann, Scholz, Tietje, & Haan, 2005; Weidema et al., 2004). Methodologies with structured framework for scenario-based LCA have been presented accordingly (Fukushima & Hirao, 2002), suggesting integration of LCA with scenario analysis is an important factor for bringing life cycle perspective into final decision-making.

As identified by The Society of Environmental Toxicology and Chemistry (SETAC) Europe Working Group, there are two principal approaches for scenarios in the context of LCA studies: what-if scenarios and cornerstone scenarios, respectively (Weidema et al., 2004). What-if scenario analysis compares two or more options in a well-known situation when the researcher is familiar with the decision problem and is able to define a scenario based on existing data and knowledge. This is especially useful for studies where specific changes within the present system need to be tested and their environmental impacts need to be studied. For example, results of a what-if scenario analysis can suggest that alternative A is better than alternative B by x%. However, number of scenarios increases when complex future situations are discussed, the decision-making becomes unmanageable.

The cornerstone scenario approach provides several options to get an overall view of the studied field and serves as a basis for the future. This approach is usually used to increase understanding for long-term studies, providing strategic information for making decisions. The cornerstone scenario approach can point out a potential direction for future development. Cornerstone scenario analysis acts as a tool for long-term planning, and the information obtained is more strategic than that obtained through the what-if scenario approach. **Figure 2-2** summarizes the cornerstone and what-if approaches showing the complexity and time dimensions of the application area in LCA studies. If the research problem is specific and covers a short to medium time frame, what-if approaches are typically used. Once the time axis is elongated and the problem area becomes more complex, cornerstone approach might be more suitable.

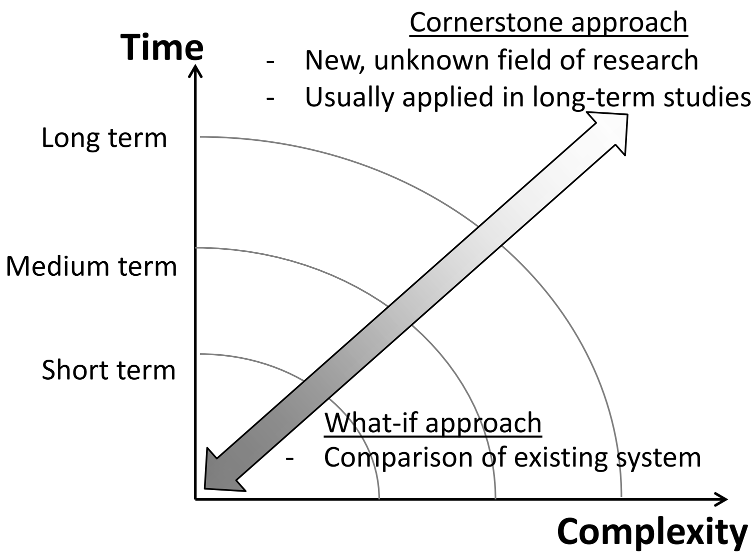


Figure 2-2 Two approaches to scenario development in life cycle assessment research

(Adapted from Weidema et al., 2004)

2.3 Scenario analysis for future studies

The development of future policy is full of complexity. In addition, up the development of future policy is uncertainties and unpredictabilities. For example, by implementing energy-efficient technologies on the demand side and less-emission technologies on the supply side, many options can lead to the same sustainable energy system. Became the future of society and environment largely depends on population, economic growth, technological change or environmental policies, the uncertainty and unpredictability of these key determinants will contribute to numerous pathways toward the future state.

In order to deal with such complicated situations, scenario analysis has been used to manage risks and develop robust strategic plans while facing an uncertain future (Hannah & Gabner, 2008; Mietzner & Reger, 2005). Scenario analysis has helped to identify the relationship between the past, present and future. Moreover, it highlights the opportunities, risks, and trade-offs during policy planning. In addition, scenario analysis can focuses on the area of greatest uncertainty for a country or an operation, and systematically develop alternative pathways in which the operation might be implemented, then further determines how these alternative pathways would be affected decision-making. Many national-level policies have implemented this analysis method to make strategic decisions. For example, in order to help policy-making, several future renewable energy scenarios have been reviewed to explore the amount of accessible renewable energy (Martinot et al., 2007; Prakash & Bhat, 2009). The role of policy-making for future development is also pointed out by the IEA-WEO by which states: “policies to facilitate the integration of variable renewables into networks are important. Such policies can range from better planning for transmission projects to development of smart grids, the creation of demand response mechanisms and the promotion of storage technologies" ("World Energy Outlook," 2012).

In the environmental studies, "scenarios" have been defined as "images of the future, or alternative futures" that are neither predictions nor forecasts, but an alternative image of how the future might unfold (IPCC, 2008). Therefore as illustrated in **Figure 2-3**, scenarios provide a dynamic view of the future by exploring various trajectories of change that lead to a broadening range of plausible futures.

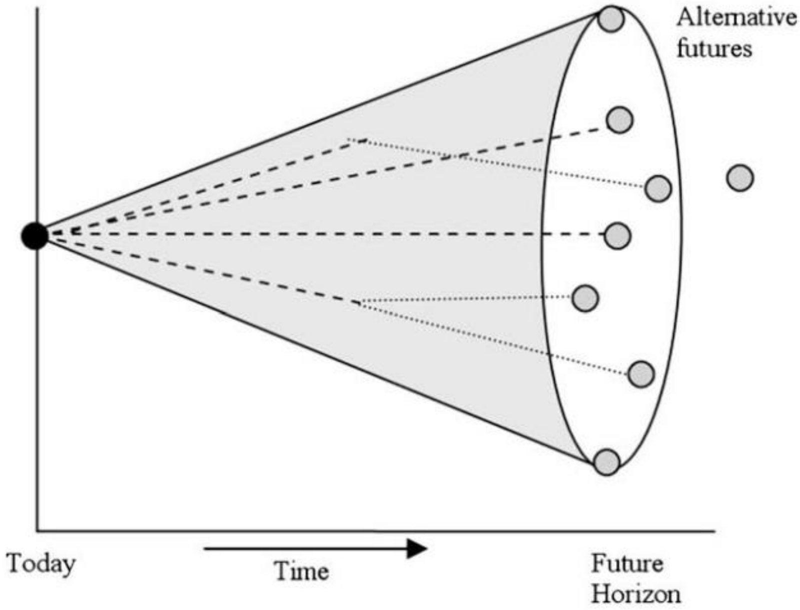


Figure 2-3 Conceptual diagram of a scenario funnel (Mahmoud et al., 2009)

Scenario analysis based on the current situation is used for both making short-term decisions and planning over long time horizons. Long-term planning is especially important when making decisions regarding the interaction factors and human factors that may impact the future (Godet & Roubelat, 1996; Slaughter, 1996). In other words, future scenarios could differ according to not only economical but also environmental, social and technological constraints and driving forces.

Table 2-1 illustrated the key factors that influence scenario generation, which are social, economic, political, technological, and environmental (SEPTE). The table can serve as a framework for identifying external forces when generating future scenarios. For example, numerous issues should be taken into consideration to achieve a sustainable energy system on shown in **Figure 2-4**. These are not issues at national levels such as energy policy, global warming, but also micro levels such as personal use behavior or spending patterns of consumers. For instance, if a government decides to introduce electric vehicles or fuel cell vehicles into a society, it is not only at the policy level but also affecting research and development of the technology. Furthermore, these issues might link to each other. Some can speed up the development as a driving force, while trade-offs and competitions might also exist. As shown in **Figure 2-5**, many options are available to be chosen for introducing an energy-saving strategy. However, a complicated situation can also turn worse if a wrong decision is made.

Although scenario analysis provides a systematic methodology framework to assess and construct different models of future situations, the complexity and huge amount of information bring challenges to decision makers when trying to distinguish the importance and relationship among various issues. After all, an effective technological decision is still not easy to be made.

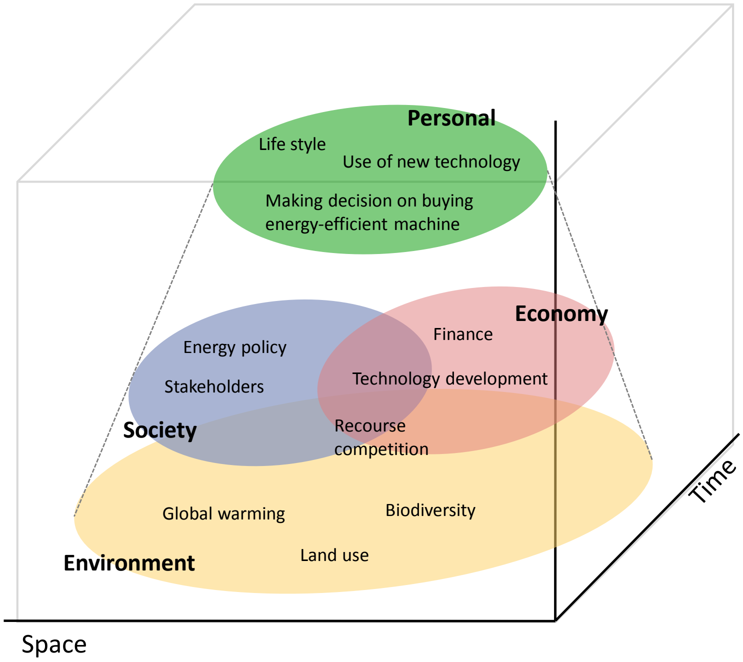


Figure 2-4 Issues belong to different dimensions in sustainable energy system

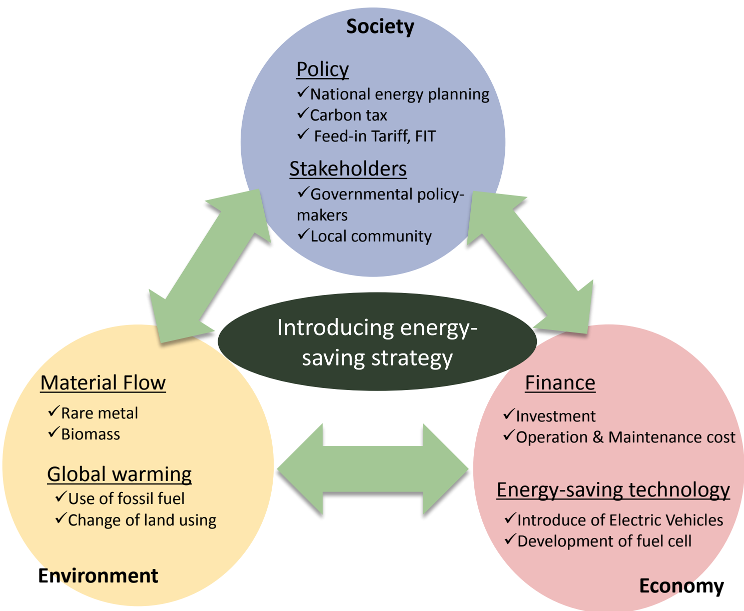


Figure 2-5 Example of issues correlated with introduce of energy-saving strategy

Table 2-1 Illustration of the key factors for generating scenarios (adapted from Wilson, 1998)

Domain	Category	Example
Social	Social Factors	Education levels, social priorities, cultural, life style, human behavior, consumer values, needs
	Demographic patterns	Age, family, household
Economic	Macroeconomic conditions	GNP, balance of trade; regional and national migration patterns; governmental expenditures
	Microeconomic conditions	Change in size, type and ownership of firms; changes in economies of scale/structure of key industries
	Market forces	Spending patterns of consumers (urban/rural, national, regional);international demand for key exports; sources of competition, resource prices
Political	Geopolitical	Trends in international relations; level of tension, conflict
	National	Changes in governmental development strategy and policy; changes in structure and responsibility of ministries; stability of government
Technological	Infrastructure	Level of technology in key industries, emerging technologies, capacity to manufacture technology for export
	Future directions	basic research and technical education trends in nations; potential for the rapid diffusion of new technologies
Environmental	Physical environment	Air/water/land pollution trends and locations, environmental quality issue(global warming)
	Natural resources	Energy prices and availability, raw materials, land use, sustainability

2.4 Summary

In Chapter 2, a scenario analysis approach and how it can be applied to future technology introduction has been reviewed and discussed. Two principal approaches in LCA studies, what-if scenario and cornerstone scenario, are identified and applied according to different future situations. It is suggested that the cornerstone scenario is suitable when evaluating a complex system.

The key factors for generating scenarios are categorized into five domains: social, economic, political, technological and environmental (SEPTE), which can serve as a framework for identifying external forces when generating future scenarios, and will be applied in this study.

CHAPTER 3 VISUALIZATION METHOD FOR TECHNOLOGY INTRODUCTION

3.1 Introduction

As described in Chapter 2, LCA is widely used to analyze the environmental impacts associated with a product or service. To complete an analysis, the product and every stage of its life cycle are explicitly described. When more than one product can deliver the same function, or more than one life cycle pathways is applicable, results of each combination of choices should be presented.

Figure 3-1 depicts a situation where N production scenarios and M use and disposal options exist for a single product. This means that there are N routes to produce a product and M pathways to utilize it. Typically when an innovation which makes P_i change into $P_{i'}$ is introduced, reduction of environmental impact is evaluated by comparing impacts associated with (P_i, U_j) and ($P_{i'}$, U_j). In this approach there are two shortcomings stemming from the limitations in the scope definition under the conventional product LCA framework. First, innovations that are not relevant with changes in inventory data would be disregarded. These innovations reduce environmental impacts without changing the inventories of the associated life cycle by increasing the availability of the product that is associated with less environmental impact. An example is the development of a new process that accepts raw materials with inferior quality. The second shortcoming is that improvements that could affect other technologies are often disregarded. In particular, it's possible that a technology made available by the evaluated innovation can i) replace other technologies that are otherwise used, or ii) let other technologies be used more, thereby reducies environmental impacts.

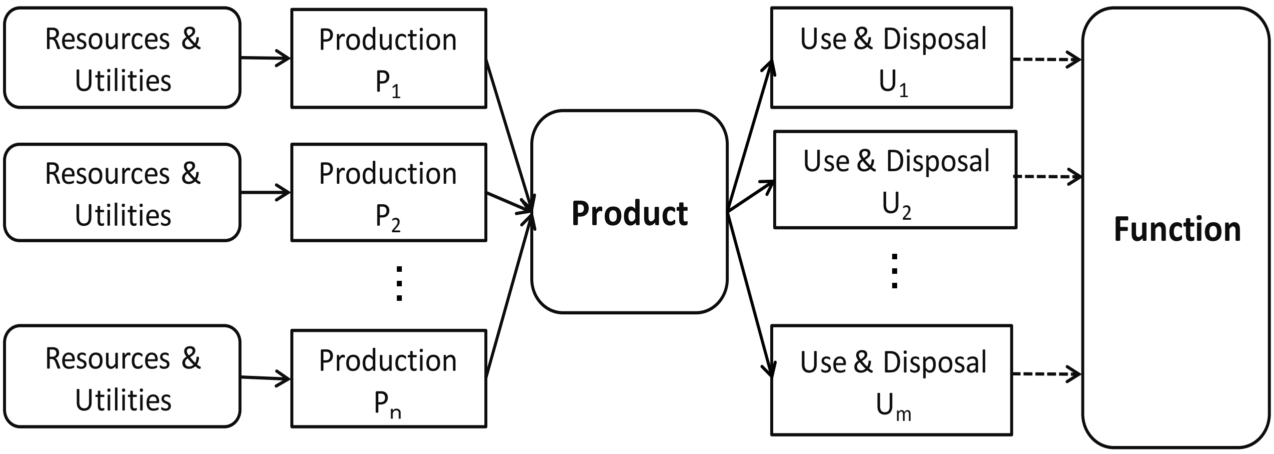


Figure 3-1 Scope of a scenario study when multiple production and use & disposal scenarios are evaluated

To support the developing of technology introduction strategies from comprehensive viewpoints that incorporate environmental and economic analyses with long-term perspectives, a graphical representation method is proposed in this study. This graphical representation could provide a more systematic view when presenting scenarios for practical decision-making. The detail steps of the methodology development are described in the following.

3.2 Visualized scenario performance and behaviors of technology introduction

When developing technology strategies, several aspects should be considered. By doing this, however, changes under each scenario would become too complicated to be identified. Scenario performance induced by interplay between technologies should be measured and presented with the comparison of trade-offs between different indices. In this section, a visualization analysis is proposed to present scenario performance and behaviors, which enables decision makers to compare and distinguish the key components in a scenario. Scenario performance will be defined by quantifiable measures such as environmental impacts or cost effectiveness, while scenario behaviors are those describing system conditions such as flexibility and operability.

3.2.1 Method of developing the graphical representation

A graphical method that evaluates a collection of technologies providing the same service or sharing the same limited resources is described in this section. **Figure 3-2** illustrates the result of individual life cycle assessment on a single technology. The P_i segment is the cradle-to-gate LCA result of a production technology P_i, while the U_j segment is the gate-to-grave LCA of the utilization technology U_j. The net environmental impact (I) is synthesized from the P_i and U_j segments.

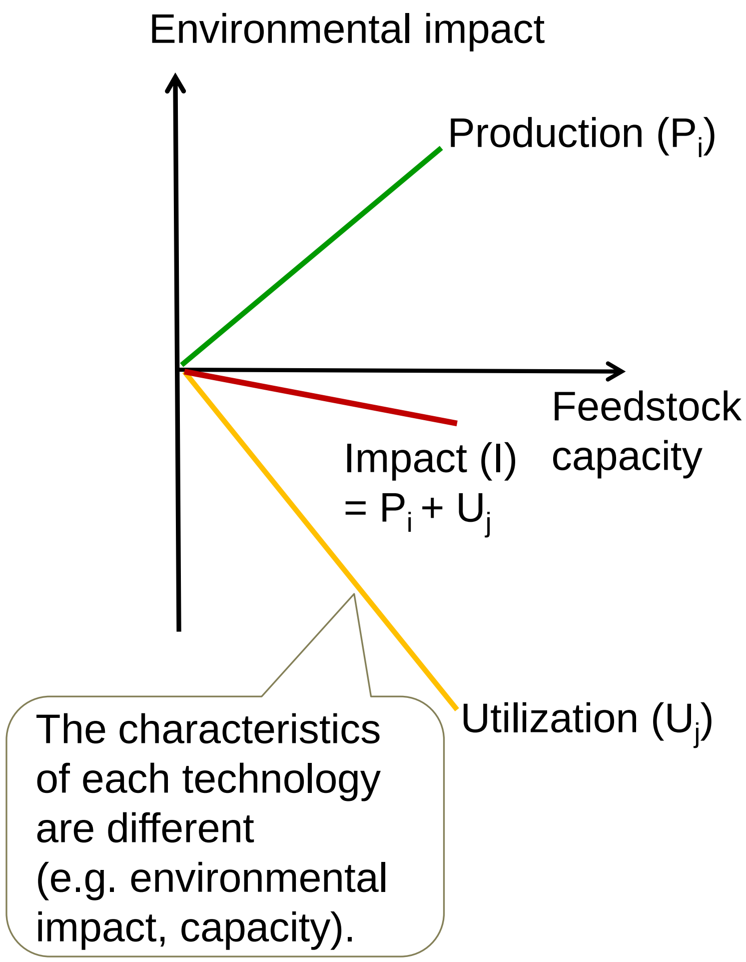


Figure 3-2 A graphical representation of individual technology

This graphical method, designed for assessing technology, is summarized in **Figure 3-3**. It presents the major building blocks of the methodology, which are in accordance with the life cycle assessment framework. There are four steps included: (1) definition of a technology domain, (2) calculation of the associated impacts of a selected domain technology, (3) generation of a graphical representation, and (4) interpretation of the results and provision of feedback information.

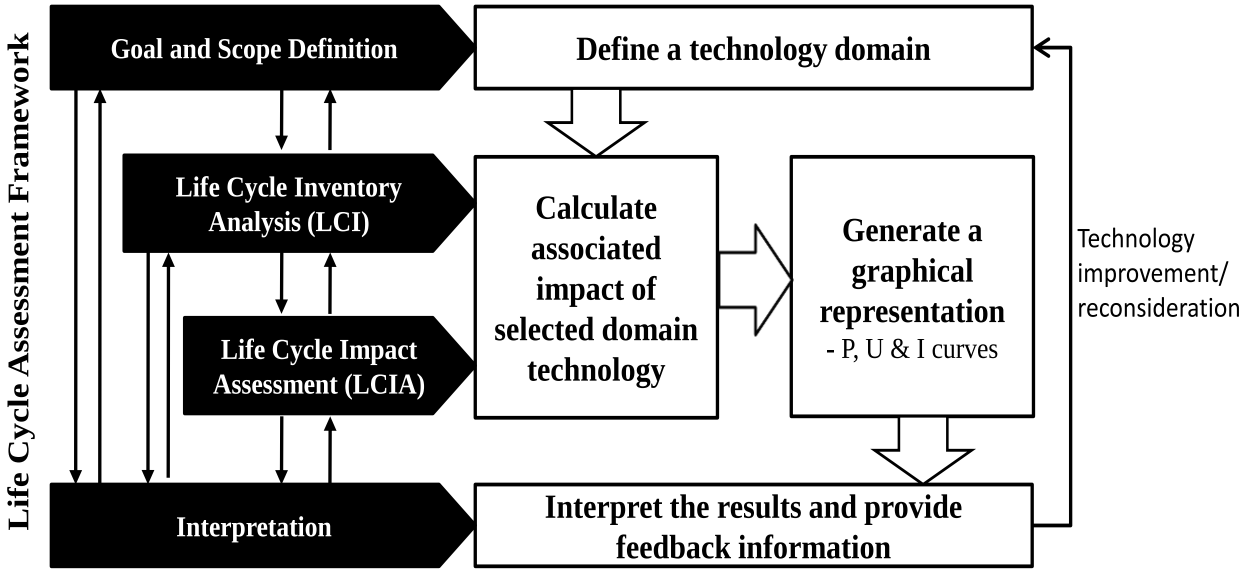


Figure 3-3 Method of developing graphical methodology within the LCA framework

Step 1: Define a technology domain

First, the evaluated technology domain has to be defined. A process of production or utilization associated with an evaluated product is defined as a technology. Each technology is classified into either production or utilization technologies. An initial collection of production and utilization technologies is set based on specific criteria and constraints. For example, "renewable hydrogen technologies" is assumed to be a technology domain that produces and utilizes hydrogen via renewable energy sources. When a technology conforms to criteria and constraints sets, for example production of hydrogen using renewable resources, this technology can be chosen in the domain. This process corresponds to the stage of "goal and scope definition" in the LCA framework.

Step 2: Calculate associated impact of selected domain technology

In the next step the environmental impacts of the selected domain technologies are calculated. Cradle-to-gate and gate-to-grave LCAs are conducted for technologies in production and utilization stages, respectively. The interrelation among technologies is not yet considered at this step, and the LCA of each of technologies is calculated separately.

A cradle-to-gate LCA is conducted for products produced by the technology to derive the environmental impact associated with the production of a unit amount of product. At the same time, resources (i.e., raw materials, land, factories for production, etc.) available for production are evaluated. To obtain the information described above, LCI and LCIA are performed.

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

Step 3: Generate a graphical representation

Next, a graphical representation can be generated using the results obtained from ***step 2***. **Figure 3-4** illustrates how an individual life cycle assessment result of a technology is assembled.

For the technologies classified in the production category, the production curve (P curve) is developed as shown in **Figure 3-4**. Each segment (P_1… P_4) represents different production technologies. A segment can be drawn in a coordinate with production and environmental impact of the primary interest in the horizontal and vertical axes, respectively. Like the production branch, these segments are also linked to form a curve that starts from the origin of the coordinate.

For the technologies classified in the utilization category, the utilization curve (U curve) is developed. Each segment (U_1… U_4) represents different utilization pathways. A U segment can be drawn in a coordinate with production and reduction of environmental impact of the primary interest in the horizontal and vertical axes, respectively. The segments are linked to form a curve that starts from the origin of the coordinate. For example, U in **Figure 3-4** depicts how a U curve would appear.

When the segments are linked in the order of their gradients (i.e. P_1, …, P_4 and U_1, …, U_4), the minimum environmental impact (P_{min}) and maximum environmental impact reduction (U_{max}) curves are constructed, respectively. This can also be described as **Equation 3-1** and **3-4**. The minimum impact (I_{min}) curve is then synthesized from P_{min} and U_{max} curves. Similarly, the segments can also be linked into curves in the reverse order of gradients (i.e. P_4, …, P_1 and U_4, …, U_1) that results the maximum environmental impact (P_{max}) and minimum environmental impact reduction (U_{min}) curves as described explicitly by **Equations 3–2** and **3-5**. P_{max} and U_{min} are then used to synthesize the maximum environmental impact (I_{max}) curve. Actual combinations of production and utilization technologies would fall in the area between P_{max}–P_{min} and U_{max}–U_{min} curves, respectively. Therefore, the actual situation of overall technological combination is the area of I_{max}-I_{min}. That is, the following applies.

$$P_{\min}: f_x^n = I_{prod,n}(x - x_n) + \sum_{k=1}^{n} I_{prod,k}(x_k - x_{k-1})$$ Equation 3-1

$$P_{\max}: f_x^n = I_{prod,n}(x - x_{N-n+1}) + \sum_{k=N-n+1}^{N} I_{prod,k}(x_k - x_{k-1})$$ Equation 3-2

$$x_n = x_{n-1} + S_n$$ Equation 3-3

$$U_{\max}: g_y^n = I_{util,n}(y - y_n) + \sum_{k=1}^{M} I_{util,k}(y_k - y_{k-1})$$ Equation 3-4

$$U_{\min}: g_y^n = I_{util,n}(y - y_{M-n+1}) + \sum_{k=M-n+1}^{M} I_{util,k}(y_k - y_{k-1})$$ Equation 3-5

$$y_n = y_{n-1} + D_n$$ Equation 3-6

where

x: variable representing production technology

y: variable representing utilization technology

n: technology type, $n \in N$

f_x^n: function for generating production segment

g_y^n: function for generating utilization segment

N: number of production technologies

M: number of utilization technologies

S_n: product supply by technology type n

D_n: product demand by technology type n

$I_{prod,n}$: unit impact associated with production technology type n, $I_{prod,1} \leq I_{prod,2} \ldots \leq I_{prod,k} \leq \ldots I_{prod,N}$

$I_{util,n}$: unit impact associated with utilization technology type n, $I_{util,1} \leq I_{util,2} \ldots \leq I_{util,k} \leq \ldots I_{util,M}$

$x_0 = 0$, $y_0 = 0$

Note that only the impacts directly associated with the individual technologies in the evaluated domain are being evaluated here. For example, the I_{max} and I_{min} curves indicate the maximum and minimum environmental impacts induced by these set of technologies. That means for a certain amount (x_h) of feedstock utilized, the environmental impact induced from society lies within the vertical range between the I_{max} and I_{min} curves at the horizontal coordinate x_h. The extent of x_h would depend on various socio-economic factors of market penetration, such as cost, incentives introduced by the government, and oil price. In this graphical representation, the fact that marginal additional impact (and impact reduction) varies over the demand of production and utilization is expressed as the shape of the region between the I_{max} and I_{min} curves.

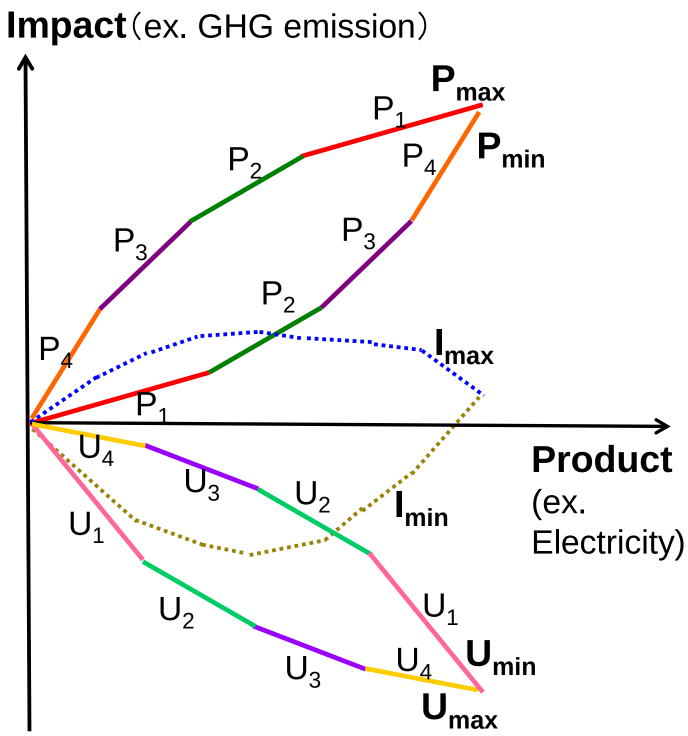


Figure 3-4 Visualization of environmental performance described by equations 3–1to 3–6 at M=4 and N=4

Scenario behaviors such as system operability and flexibility are described in **Figure 3-5**. The vertical segment between the maximum and minimum impact points represents the operability at amount of product supply x_a. A longer vertical segment suggests more options can be chosen in the system. On the other hand, the horizontal segment represents the flexibility of the system. In the case of shifting x_a right to x_b, it shows that production is still sufficient because it is still in the area of P_{min}–P_{max}. In other words, the system has shown flexibility in the technology implementation. However, system operability would become smaller upon this technology implementation. The visualized comparison between operability and flexibility provides a simple evaluation method for decision makers when they design and operate a system.

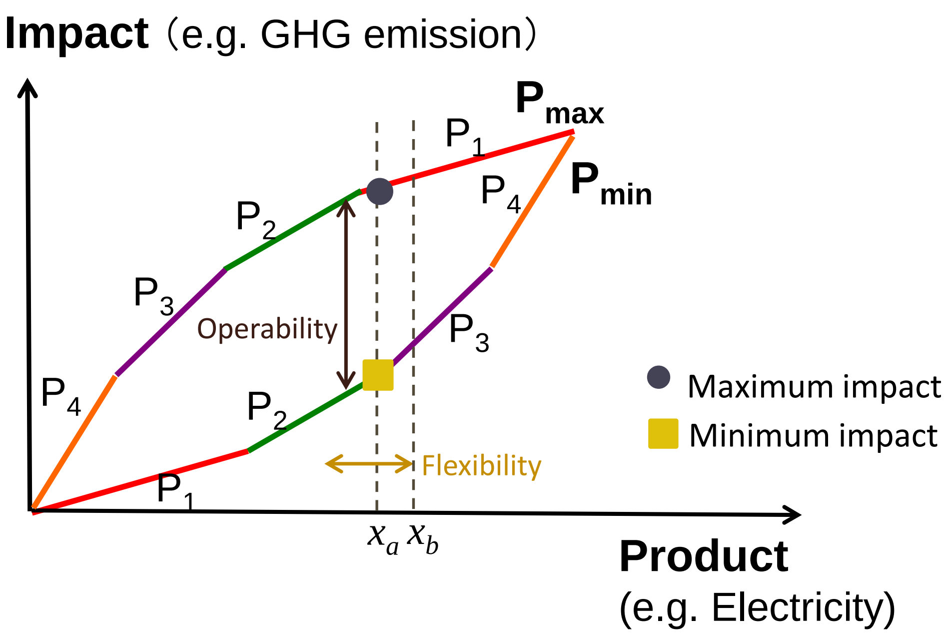


Figure 3-5 Variation of impacts by implementing production technologies

Step 4: Interpret the results and provide feedback information

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

In order to provide an easy way to communicate, the representation method is implemented on Microsoft® Office Excel described in VBA (Visual Basic for Application) code which is attached in the appendix.

3.2.2 Indicators

To characterize the results from this methodology, indicators are proposed as shown in **Figure 3-6**. The feedstock Point A (x_A, y_A) indicates the maximum environmental impact (i.e., y_A) induced by the chosen technologies among all possible technology implementations. As a convex upward curve, point A on the I_{max} curve indicates the highest point and implies the maximum possible environmental impact.

Then point B (x_B, 0) can give an index of emission neutralization. As shown in **Figure 3-6,** the y value (i.e., environmental impact) of the I_{max} curve will be maintained as negative when the hydrogen amount is over point B (i.e. x_B). In other words, when the feedstock amount exceeds x_B, the environmental impact reduction can always be achieved.

Finally, at point C, the maximum emission reduction can be expressed. On account of point C (x_C, y_C) being on I_{min} curve and showing the lowest point, point C can indicate the maximum emission reduction amount (y_C) and the most appropriate amount (x_C) for society attributable to the highest reduction potential. Even if the feedstock utilization exceeds x_c, the environmental impact remains negative compared to the benchmark situation at the origin of the figure.

Figure 3-6 also shows the feasible region that is encompassed by the I_{max} and I_{min} curves. The feasible region presents all potential consequences of energy technology introduction, which distinguishes the uncertainty by the choice of technologies. This approach is particularly useful for assessing different scenarios of the technology implementation. In this way, stakeholders (ex. technology developers and policy makers) can focus on visions of the future society, which include different choices of sets of technologies.

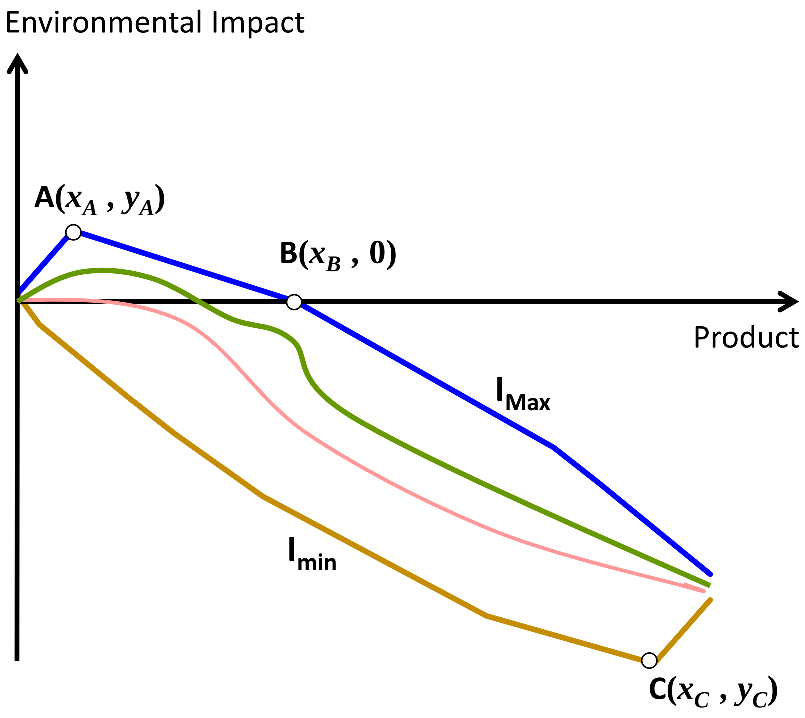


Figure 3-6 Scheme of indicators applicable to graphical representation

3.2.3 Contribution of technology innovation/breakthrough

This proposed methodology can also be used to evaluate a technology breakthrough/improvement. The composite of technologies including the evaluated innovation can be constructed by changing or adding segments in the P and U curves. Examples of modification of P_{min} and U_{max} curves owing to various types of innovation are shown in **Figure 3-7**, with including the extension in capacity of P_1 (dotted line in P'), improvement in efficiency of P_3 (P_3' of P') and new technology or technical innovation (U_N of U'). The innovation will change the curves and thus change the I_{min} curve. In the same manner, the I_{max} curve is modified, and the new indicators are obtained.

To evaluate the changes in environmental impacts for a given innovation, the three indicators (i.e. described in section 3.2.2) before and after the innovation can be compared. The system-wide environmental impact reduction by technology innovation is explored, making it possible to provide feedback to the early stage of technology design or to develop a more strategic policy.

Furthermore, this methodology can be used to assess different impact categories together with a main impact category, according to the focused interest, as demonstrated in the following case study.

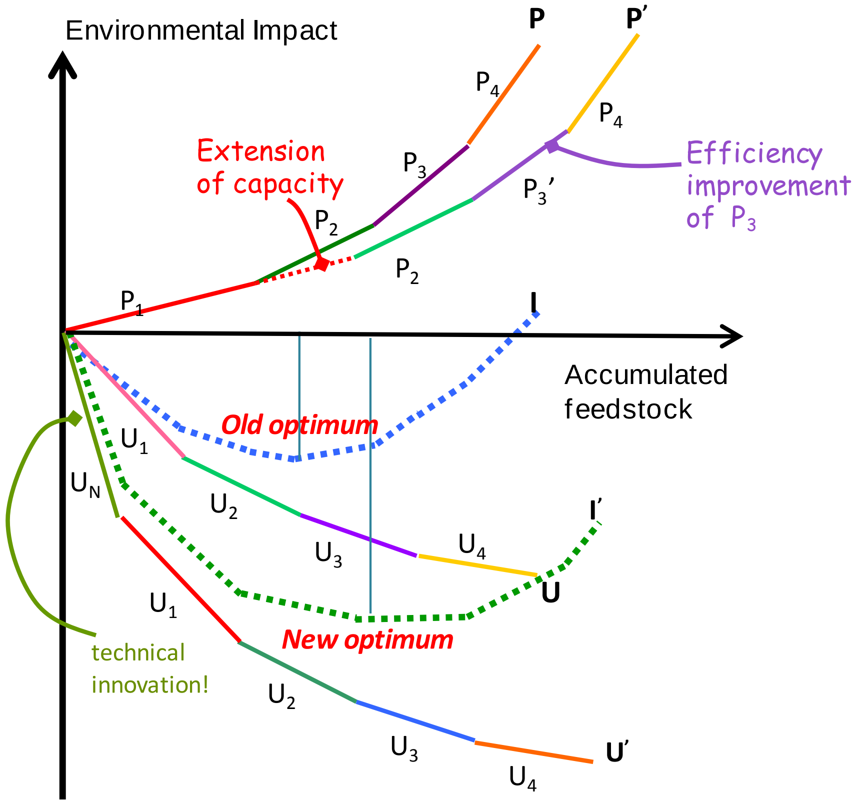


Figure 3-7 Scheme of evaluation in technology innovation

3.3 Visualization of trade-offs of different evaluation indices

When making a decision, several interests might be considered. For example, to design a process with less cost or less environmental impact is a common trade-off issue. In this study, the relation of different interests in decision-making is visualized as illustrated in **Figure 3-8** and **Figure 3-9**. With the same amount of product x_a, the environmental impact induced by production is varied. The impact in the case of cost minimum falls in the middle of the maximum and minimum values. In other words, scenarios that have the worst and best environmental performance reveal their potential in the sense of environmental impact reduction by the choice of technology implementation.

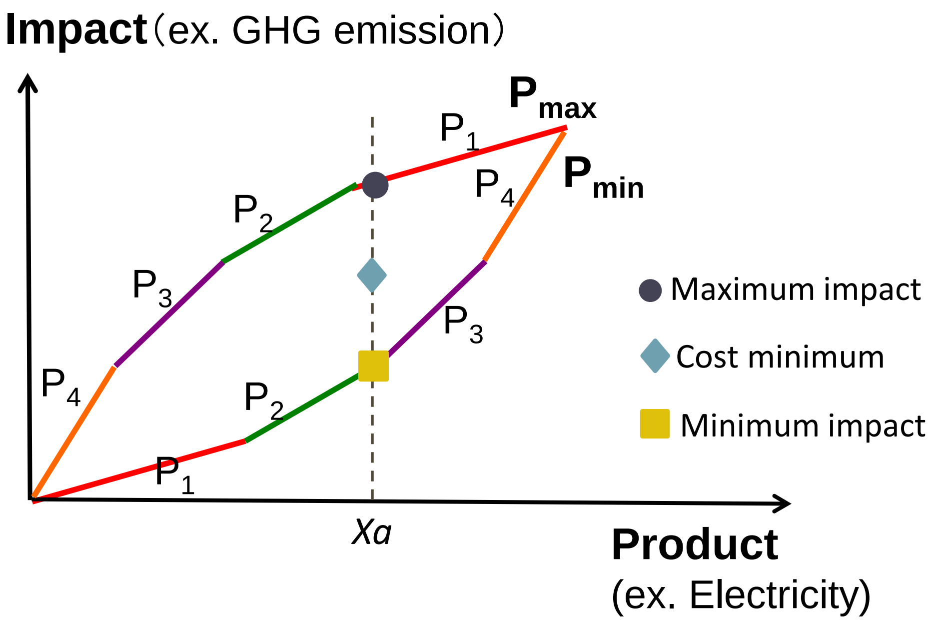


Figure 3-8 Visualization of variation of impact by implementing production technologies

The relationship between two indices (e.g. cost and environmental impact) is visualized as illustrated in **Figure 3-9**. Maximum and minimum cost and CO_2 emission are calculated for the amount of product x_a. The area encompassed by the points represents the attainable region. Multi-objective optimization is applied to define the boundary of the attainable region by **Equation 3-7**, **Equation 3-9** and **Equation 3-9**. A detailed explanation is presented in **Table 3-1**. Here, each calculation is on a one-year basis for both cost and CO_2 optimization. The points on the different regions feature the option of technology combination. **Region LL** in **Figure 3-9** shows the trade-off between environmental impact and economic expense, while **region MM** cautions a worse–worse condition that should be avoided. Although the ranges depict the scenario extremes that can be reached, arranging the information in this way, such as scenario grouping by systematic discussion and analysis, will be helpful for strategic policy making.

$$\underset{v}{optimize}(OF(r,v)) \quad \text{Equation 3-7}$$

$$\mathrm{Cost}_{\max} = \max_{v}(\sum_{y}^{\mathrm{T}} \mathrm{Cost}_{y}(n)) \quad \text{Equation 3-8}$$

$$\mathrm{CO}_{2\max} = \max_{v}(\sum_{y}^{\mathrm{T}} \mathrm{CO}_{2y}(n)) \quad \text{Equation 3-9}$$

where

v: variables in energy system

$Cost_{max}$: the pattern of technology combination that results in maximum total cost

$CO_{2\,max}$: the pattern of technology combination that results in maximum CO_2 emission

y: conditions in year y

T: considered year

r: 0, 0.1, 0.2…1.0, where $0 \le r \le 1$

Table 3-1 Summary of equations to generate boundary conditions of attainable regions

Optimize	OF(*r,v)*	The boundary condition of the attainable region	Reference
Minimize	$r\dfrac{\sum_{y}^{T}\mathrm{Cost}_y(n)}{\mathrm{Cost}_{\max}}+(1-r)\dfrac{\sum_{y}^{T}\mathrm{CO}_{2y}(n)}{\mathrm{CO}_{2\max}}$	Less cost and less CO_2	LL
Minimize	$r\dfrac{\mathrm{Cost}_{\max}-\sum_{y}^{T}\mathrm{Cost}_y(n)}{\mathrm{Cost}_{\max}}+(1-r)\dfrac{\sum_{y}^{T}\mathrm{CO}_{2y}(n)}{\mathrm{CO}_{2\max}}$	More cost and less CO_2	ML
Maximize	$r\dfrac{\mathrm{Cost}_{\max}-\sum_{y}^{T}\mathrm{Cost}_y(n)}{\mathrm{Cost}_{\max}}+(1-r)\dfrac{\sum_{y}^{T}\mathrm{CO}_{2y}(n)}{\mathrm{CO}_{2\max}}$	Less cost and more CO_2	LM
Maximize	$r\dfrac{\sum_{y}^{T}\mathrm{Cost}_y(n)}{\mathrm{Cost}_{\max}}+(1-r)\dfrac{\sum_{y}^{T}\mathrm{CO}_{2y}(n)}{\mathrm{CO}_{2\max}}$	More cost and more CO_2	MM

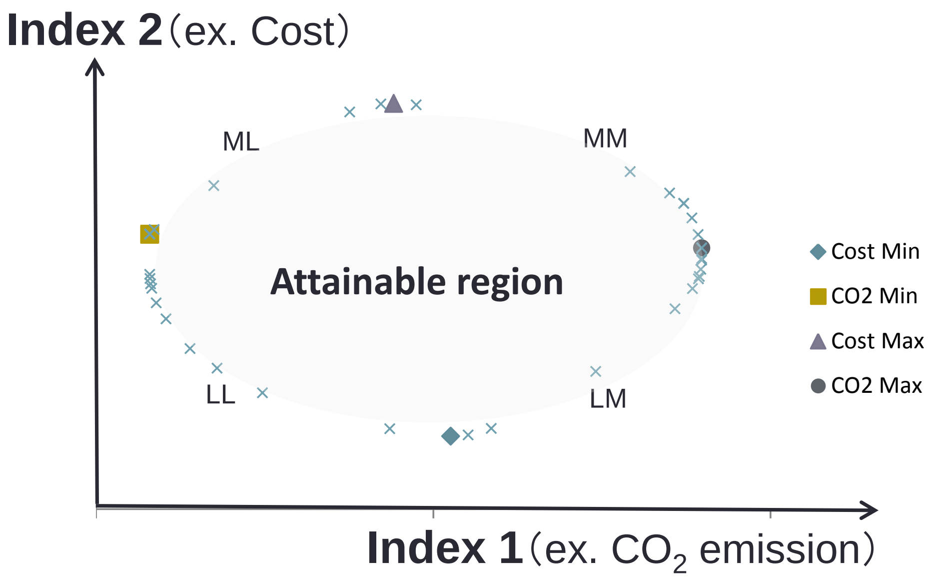


Figure 3-9 Visualization of relationship between two indices (cost and environmental impact as examples)

The further discussion can be fallen on the scenario grouping. **Figure 3-10** is performing a possibility for making better decisions by grouping scenario under different required criteria. Based on the visualized information, it is possible to generate an insightful decision based on the results. Decision makers can compare different scenario performances and behaviors with the discussion of focused evaluating indices and select preferable decisions.

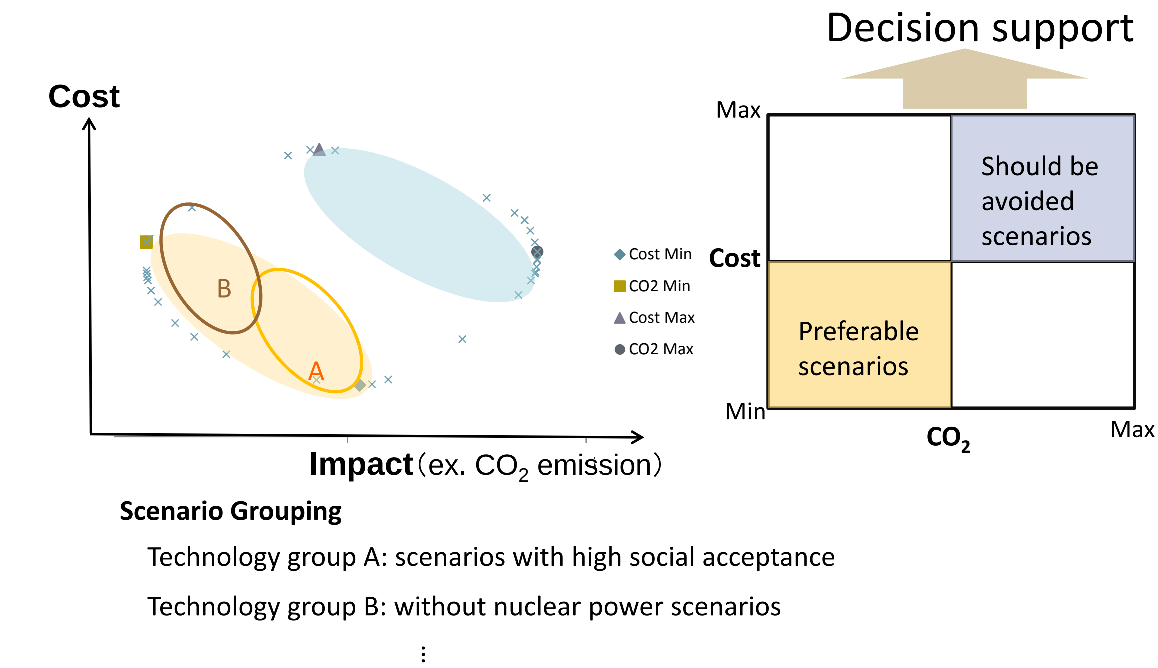


Figure 3-10 Scenario grouping for supporting decision making

3.4 Projection of future conditions

Time plays an important role in analyzing system transitions from the present to the future. Since it is impossible to predict future conditions perfectly, representative scenarios should be developed based on specific social conditions and activities (i.e. future energy consumption, composition of electricity generation, policy and so on). As **Equations 3–8** and **3–9** illustrate, scenario consequences are analyzed in long-term projections. This method allows visualization of the different consequences between the present and the future, which makes it easier to observe technology transitions and possible technological innovations.

3.5 Discussion and limitations of the visualization method

The proposed methodology distinguishes uncertainty for the choice of technologies. This approach is particularly useful for assessing different scenarios of technology implementation. Both existing and new technologies can be assessed in the proposed framework. However, varied levels of uncertainty in the existing and new technologies should be noted, but currently not assessed in the proposed methodology.

Furthermore, the interactions among technologies are visualized in relation to the changes in environmental consequences. Namely, a technology improvement/ breakthrough may replace an original one or change the orders of environmental impacts among evaluated technologies. Indirect effects (e.g. land competition, capital allocation between technologies) are not assessed in this study, but it is possible to support the results obtained from other LCA studies to emphasize the competitiveness of certain technologies.

Currently, environmental impact of each technology is assumed as a linear segment, but it will show non-linear to if the scale effect is considered (e.g. environmental impact may be decreased if scale up effects are considered).

Moreover, when more than one environmental indices are considered, the graphical representation can be extended into three dimensions to compare two different indices, yet it is not easy to understand if it is extended into more than three dimensions. In this case, the aggregation method might be applied, although some information on the characteristics of the index may be lost by the aggregation. That is, if the selected impact categories are integrated into a single index, the differences of impacts among various processes cannot be identified. For instance, a process that emits lower GHG emission may have a higher acidification potential. If several indexes are integrated, the information on the trade-off between them might be lost.

The other approach is to visualize the single index separately. As shown in **Figure 3-11**, the orders of the candidate technologies are changed when different evaluating index are considered. Technology combinations are changed accordingly. This approach provides another viewpoint for comparing trade-off instead of simply aggregating the multiple indices.

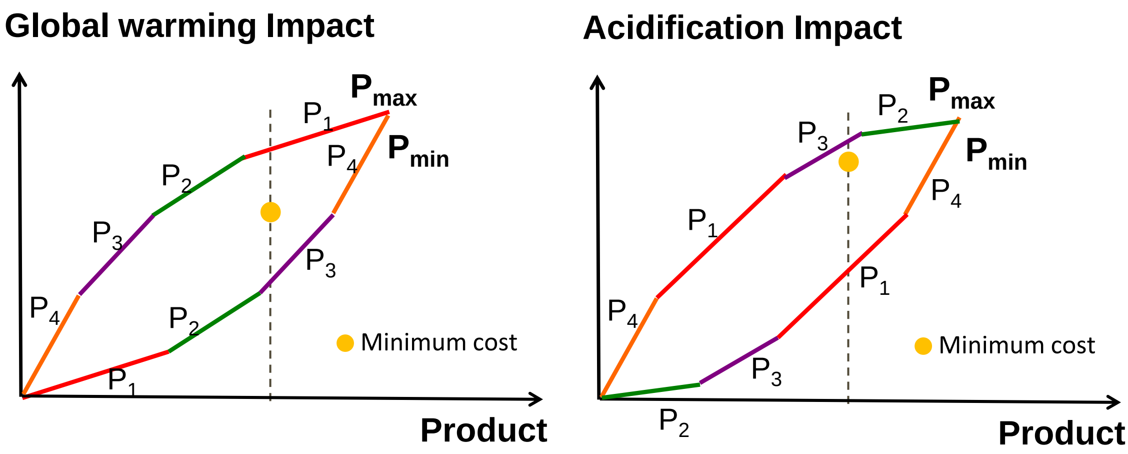


Figure 3-11 Visualization of different environmental index

3.6 Summary

Chapter 3 proposed a graphical representation to systematically evaluate the interrelations among technologies, taking into consideration of uncertainties in the choice. This approach allows analyses of the consequences of the technology introduction in three aspects as follows.

- Visualization of the theoretical range of environmental consequences assuming a set of technologies that is in the same domain. The visualization also enables identification of the range of potential consequence of a technology replacement within the defined technology domain that effectively displays marginal changes in environmental impacts induced by the technologies.

- Visualization of trade-offs of different evaluation indices. The comparison of possible future technology options within an environmental-economical context can help decision makers have a bird's-eye view in the development process.

- Visualization of system transitions in a given time frame. The visualization of different consequences between the present and the future makes it easier to see technology transitions and possible technological innovations. Limitations of the visualization method should be noted. Indirect effects between technologies are not considered under this methodology framework. The system can visualize the changes of environmental consequences induced by the variation of scale, although not considered now for the reason of simplification.

CHAPTER 4 APPLICATION TO THE DESIGN OF ENERGY SYSTEMS

4.1 Introduction

In this chapter, two case studies are presented for demonstrating the proposed graphical representation method: hydrogen-related technology in Taiwan and electricity-based system in Japan. The former one aims to assess a grassroots design (i.e. a new system) while the latter discusses different technology implementation in a retrofit design (i.e. an exist system).

In the first case study, two scenarios representing the innovative technologies in a "hydrogen society" are analyzed, which demonstrates how technology improvement is evaluated by the graphical representation method.

The second case discusses how to design a system which is based on the current situation. Electricity system is applied and is more focused on identifying the relation of different interests when a system is designed.

4.2 Case study on Taiwanese hydrogen system

4.2.1 Background

In Taiwan, the 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% for 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/km^2 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 process of energy conversion (e.g. converts the potential chemical energy of gasoline and oxygen into thermal energy). 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 unutilized and renewable energy sources because the pathways to convert these sources into hydrogen are developed actively. A research shows 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 (John Turner et al., 2008). In this way, hydrogen society could promote independence of 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 disaster-tolerant energy supply and 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 above-mentioned challenges. At the same time, Taiwan, as an island, realizes the importance of mitigating global warming and striving to reduce GHG emission, although it is not a member party of the United Nations Framework Convention on Climate Change (UNFCCC).

There is a wide range of literatures exploring different possible pathways to 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 address 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 a case study to demonstrate the graphical methodology. 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.

4.2.2 Define 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 Scenarios (S1, S2) on the choice of technologies and evaluation of technology improvement are considered, as summarized in **Table 4-1.** Technologies of renewable energy to hydrogen include: water electrolysis by wind and solar energy, and bio-hydrogen 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.

Table 4-1 Selected domain technologies for two scenarios

Scenario	**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）

Greenhouse gas (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 is to realize how technology improvement can contribute to environmental impact reduction in a systematic manner.

4.2.3 Calculate environmental impact of selected technologies and their potential

- ***Cradle-to-gate LCA in production sub-domain***

The cradle-to gate LCA is conducted to evaluate the technologies in the production subdomain: (a) water electrolysis by wind energy, (b) water electrolysis by solar energy, and (c) bio-hydrogen 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 ca. 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 a 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 the Weibull PDF can be derived. In this study, the Weibull PDF shown below is applied to simulate wind speed the respective locations.

$$f(v) = \frac{k}{c}(\frac{v}{c})^{k-1} e^{-(v/c)^k}$$ Equation 4-1

k: the shape parameter,
c: the scale parameter and
v: wind speed

The parameter *k* determines the shape of the distribution curve, and with *k*=2 is a typical pattern found at most site (Patel, 2006). And the parameter c represents the wind speed range. For the greater value of *c*, the distribution curve shift right to higher wind speed, that is, higher *c* represents the greater number of days that have high winds. One of the simulated results is shown in **Figure 4-1**.

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_I and V_O. P(*V*) is actual power output, P_R is the constant output at a range of rated speed V_R and cut-off speed V_O,

$$\mathrm{P}(V) = \begin{cases} 0 & , V < V_{\mathrm{I}} = 3(m/s) \\ (a_1 V^3 + a_2 V^2 + a_3 V + a_4) \cdot P_{\mathrm{R}} & , V_{\mathrm{I}} \le V < V_{\mathrm{R}} = 15(m/s) \\ P_{\mathrm{R}} & , V_{\mathrm{R}} \le V < V_{\mathrm{O}} = 25(m/s) \\ 0 & , V \ge V_{\mathrm{O}} \end{cases}$$ Equation 4-2

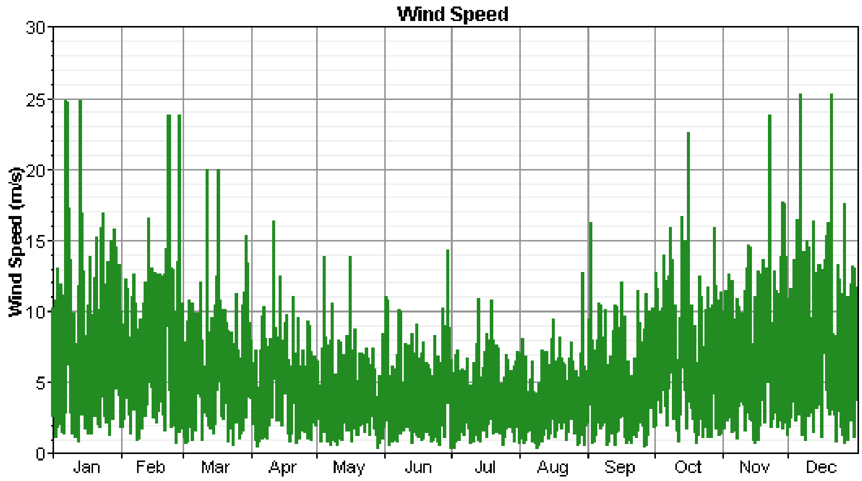


Figure 4-1The simulation of wind speed distribution over one year

Using regression analysis, values for all the parameters were obtained as follows: a_1=-0.001, a_2=0.030, a_3=-0.176, a_4=0.292, P_R=1026 (kW). Then by applying simulated hourly wind speed at respective wind turbine sites throughout a year into the function obtained, namely, P(V) =0 when $V \leqq$ (3m/s) and $V \geqq$ 25(m/s), P(V)= 1026 × (-0.001V^3+0.030V^2-0.176V+0.292) when 3 ≦ V<15(m/s), and P(V)=1026 when 15 ≦ V<25(m/s), respective power generation were obtained. Then, by applying a simulated hourly wind speed at respective wind turbine sites throughout a given year, respective power generations are obtained.

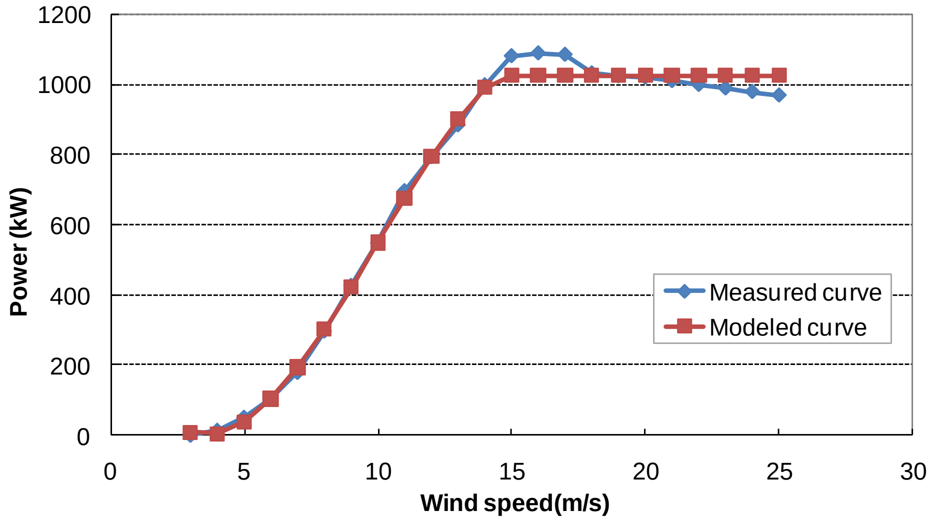


Figure 4-2 Measured and modeled characteristic curve

Commercialized process data (53.4 kWh/kg-H_2) (Ivy 2004) is 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 & Mann, 2004; Lee & 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.

$$E_{\mathrm{PV}} = \sum_i (P_i \times A_i) \qquad \text{Equation 4-3}$$

where

E_{Pv} :PV power generation (kWh/year)
i: cities, counties
P_i : Power production per m^2 in a year in city or county I (kWh/m^2.year), Pi is related to solar irradiation at each location
A_i : Residential building roof area in city or county I (m^2)

The environmental impact of solar-derived hydrogen is calculated from the life cycle inventory data of PV module production provided from the literature (Alsemal & Wild-Scholten, 2006), and then combining with an electrolysis process (Ivy, 2004).

(c) Biohydrogen production using sugarcane

In this study, sugarcane is chosen as feedstock to generate hydrogen. Two different production processes, i.e. dark fermentation and two-stage process, are evaluated (Manish et al., 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. The GHG emission from electricity is calculated by emission factor (0.637 kg-CO_2e/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 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-CO_2e/kWh. To calculate this value, the Taiwanese power structure is taken into account (Fukushima & Kuo, 2008).

➢ ***Gate-to-grave LCA in utilization sub-domain***

The demand for hydrogen in the transportation sector is calculated by estimating the average commute distance in a year (km/year) for each type of vehicle (i.e. Trucks, passenger cars, and motorcycles), then multiplying with the fuel consumption rate (kg-fuel/km) to convert into fuel consumption (Ministry of Transportation and

Communications, 2009; ITRI , 2005).

GHG emission in transportation sector is calculated based on Intergovernmental Panel on Climate Change (IPCC) guideline using the following equation (IPCC, 2007).

$$E_{CO_2} = \sum_j E_{CO_2,j} = \sum_j \left(\frac{N_j D_j}{M_j} \times EF_{CO_2}\right) \qquad \text{Equation 4-4}$$

Where

E_{CO2}: Total CO_2 emission (kg-CO_2e)
N_j : Number of vehicles j
D_j : Average travel distance of vehicle j (km)
M_j : Average fuel consumption rate of vehicle j (km/L-fuel)
$EF_{CO2,j}$: CO_2 emission factor for fuel used in vehicle j (kg-CO_2e/L-fuel)
j: Passenger car, motorcycle, trucks

Therefore, if a 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 the assumption that trucks are fueled by diesel, while passenger cars and motorcycles are by fueled 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 negative environmental impact, because only fuel replacement is considered.

Each LCA and LCI results of the selected technologies are calculated and summarized in **Table 4-2**. In production technologies, the highest environmental impact is induced by dark fermentation, whereas the lowest environmental impact is by two-stage process. In utilization technologies, diesel-fueled vehicles have lower fossil fuel combustions considering the unit traveling distance.

Table 4-2 Life cycle inventory results of hydrogen related subdomain technologies (production and utilization)

	Process	**GHG emission (a)** ($kg\text{-}CO_2e/kg\text{-}H_2$)	**Capacity (kton)(b)** ($kg\text{-}CO_2e/kg\text{-}H_2$)	**Total GHG emission (a)×(b)** ($kton\text{-}CO_2e$)
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

4.2.4 Generate graphical representations

The results summarized in Table 4-2 are used to generate graphical representations. Data presented in production and utilization subdomains are used to construct P and U curves, respectively. Then, the two curves are combined to synthesize I curve, which shows the net environmental impacts over the extent of the technology domain. **Figure 4-3** shows the minimum and maximum environmental impact patterns of scenario 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}, U_{min}) appears when all the technologies are introduced in the opposite order.

The three indicators for scenario S1 are shown in **Figure 4-3** as well. Point 1 represents a "Maximum emission reduction", which has a potential of 8.31 Mton-CO_2e when 0.42 Mton-H_2 is utilized. "Maximum environmental impact" shown as point 2 is 4.81 Mton-CO_2e, indicating that the largest emission might be generated by utilizing the domain technologies, and "Emission neutralization" is achieved when 0.36 Mton-H_2 is utilized, shown as point 3. A similar procedure can be applied to scenario S2.

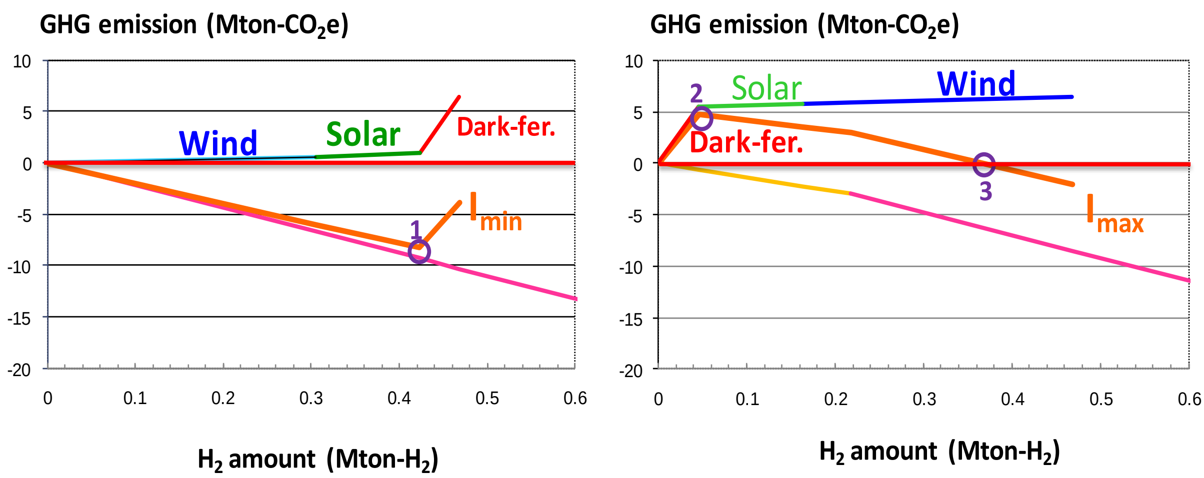


Figure 4-3 Minimum (left) and maximum (right) environmental impact patterns of S1

Figure 4-4 summarizes the technologies included in the assessment. **Figure 4-5** shows the comparison between scenarios S1 and S2 based on the minimum environmental impact pattern. The results of S1 are presented as solid lines, and the dotted lines are for S2. As stated in **Table 4-2,** two-stage process has the lowest environmental impacts among all hydrogen production subdomain technologies. Therefore, the order of introducing production subdomain technologies in S2 is changed from S1. **Figure 4-5** also demonstrates the interactions among hydrogen production subdomain technologies. In case of S2, biohydrogen production process becomes the most preferential technology, which makes sugarcane biomass utilized earlier than wind and solar resources. The yield of hydrogen production is enhanced, and the impact curves are changed (I_{min}_S1→I_{min}_S2).

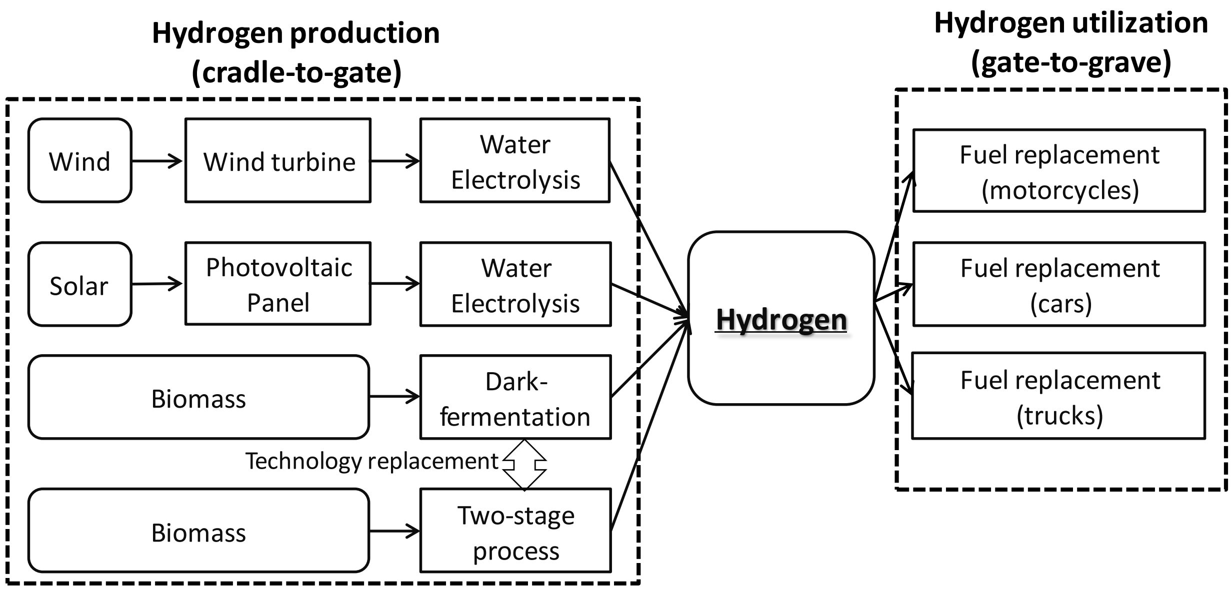


Figure 4-4 Scope of assessed hydrogen technologies in the case study. Here, the cradle-to-gate of hydrogen production technologies (ex. wind turbine manufacturing and installation) are considered, while in utilization domain, only fuel replacement is considered.

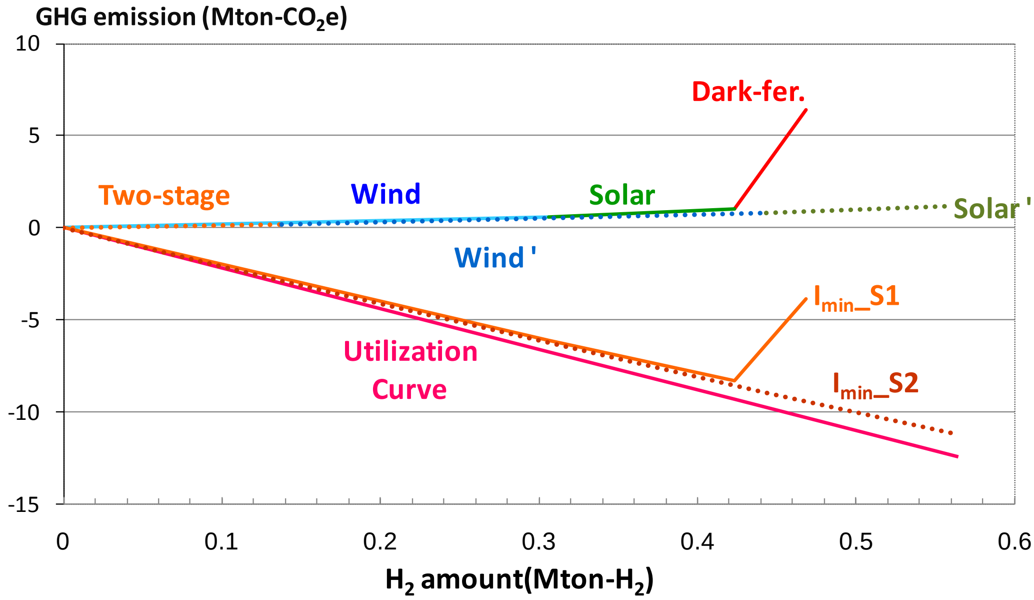


Figure 4-5 Comparison of S1 (solid lines) and S2 (dotted lines) with minimum environmental impact pattern

Figure 4-6 shows the comparison result of indicators between S1 and S2. The three indicators, maximum emission reduction (0.42, -8.31), maximum environmental impact (0.05, 4.81), and emission neutralization (0.36, 0), are discussed in S1. S2 only shows one indicator "maximum emission reduction" located on (0.56, -11.16), which indicates that 11.16 Mton-CO_2e emission can be reduced when 0.56 Mton-H_2 is utilized. The results illustrate that the introduction of a two-stage process will always reduce environmental impact because the environmental impact is negative at every point on 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. There are 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 choices made in society, the environmental impacts in the futures under S1 and S2 can be anywhere in the range surrounded by the respective I_{min} and I_{max} curves. As all the indicators show S2 has a better collection of technologies, S2 seems to be the better choice. The reduction in environmental impact in S2 is assured, while in case of S1 there is a possibility to have increase in environmental impact. Likewise, 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 two-stage hydrogen fermentation process.

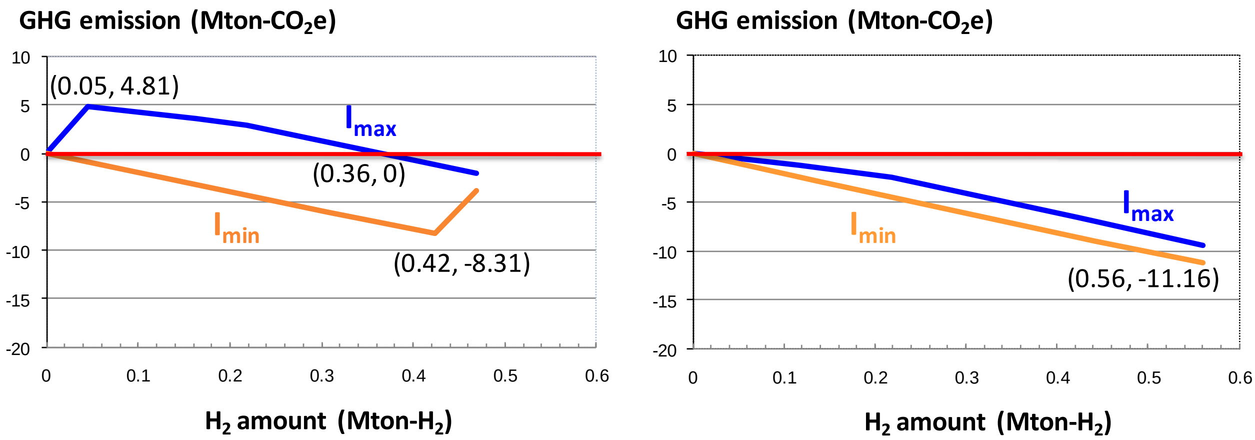


Figure 4-6 Comparison of indicators between S1 (left) and S2 (right)

4.3 Case study on Japanese electricity system

Applications of the graphical representation method are demonstrated by discussing scenarios of implementing various energy technologies in the Japanese electricity system. In this case study, scenario performance and behavior at present (year 2010) and for future projections (year 2050) are evaluated by the proposed visualization analysis.

4.3.1 Background

To help solve energy security and global warming issues, the Japanese government made a decision to shift the current structure to a less fossil fuel-reliant society. The Japanese Cabinet adopted a new Basic Energy Plan in June 2010 (METI, 2010a), making the target to shift to a system that generates electricity almost solely from nuclear power and renewable resources, and provides a 30 percent reduction in energy-related greenhouse gas (GHG) emissions by 2030. It was seen as a solution for Japan because energy independence can be increased, and at the same time, effectively decrease GHG emissions. However, since the devastating earthquake and nuclear power disaster of March 2011, the energy policy has been facing challenges and needs to be revised and redesigned. Under such conditions, some researchers suggested that Japan should take advantage of this opportunity to transform into a more sustainable society (Fukushima et al., 2011).

Therefore, the objective of the case study is to provide a systematic evaluation of Japanese energy systems using the visualization method, aiming at supporting the redesign of energy policy. The Japanese energy system includes a wide range of technologies in electricity, heat and fuel systems, whereas we focus only on the discussion of electricity systems in this case study. The electricity system in Japan before the earthquake was composed of generation technologies such as hydropower, geothermal, nuclear, gas combine cycle (GCC), and natural gas-fired (LNG), oil-fired, and coal-fired plants. Almost 60% of power is generated by fossil fuel-fired plants, which mainly rely on imports, and at the same times are a major concern as a huge GHG contributor (METI, 2011). In this case study, the Japanese electricity system before the earthquake and several scenarios under different conditions will be assessed using the proposed visualization method.

In energy systems design, market mechanism and cost-effective optimization method are often used for technology implementation planning (Berrie & Anari, 1986). However, not only economical but also environmental, social and technological constraints and driving force can affect the combination of technologies in a system. For example, renewable energy-based power generation technologies are willing to be used under policy changes (e.g. subsidy, carbon tax, etc.). To tackle such a complex problem by assisting sustainable system design, a comprehensive assessment with various perspectives plays an essential role in strategic policy decision.

4.3.2 Define technology domain

In this step, the evaluation boundary (i.e. technology domain) is selected as electricity technologies in Japan, and two subdomains are included as follows. (1) Production subdomain: electricity supply from hydropower; geothermal; nuclear; gas combine cycle (GCC); natural gas-fired (LNG), oil-fired (Oil), and coal-fired (Coal) plants; photovoltaic (PV) solar energy; and wind turbines (WTs). (2) Utilization subdomain: electricity demand. Scenarios that include renewable energy (PVs, WTs) are introduced aggressively to reduce the dependency on fossil fuel until year 2050. In the utilization subdomain, conventional vehicles are replaced by plug-in hybrid vehicles (PHV), and electric vehicles (EV) replace conventional vehicles in the transportation sector.

GHG emission is selected as the main evaluation indicator of environmental impact. The total GHG emission induced from technology combinations at each target year is calculated to compare the resulting changes. Power generation cost is another evaluation indicator in this case study, showing the economic performance of the scenarios.

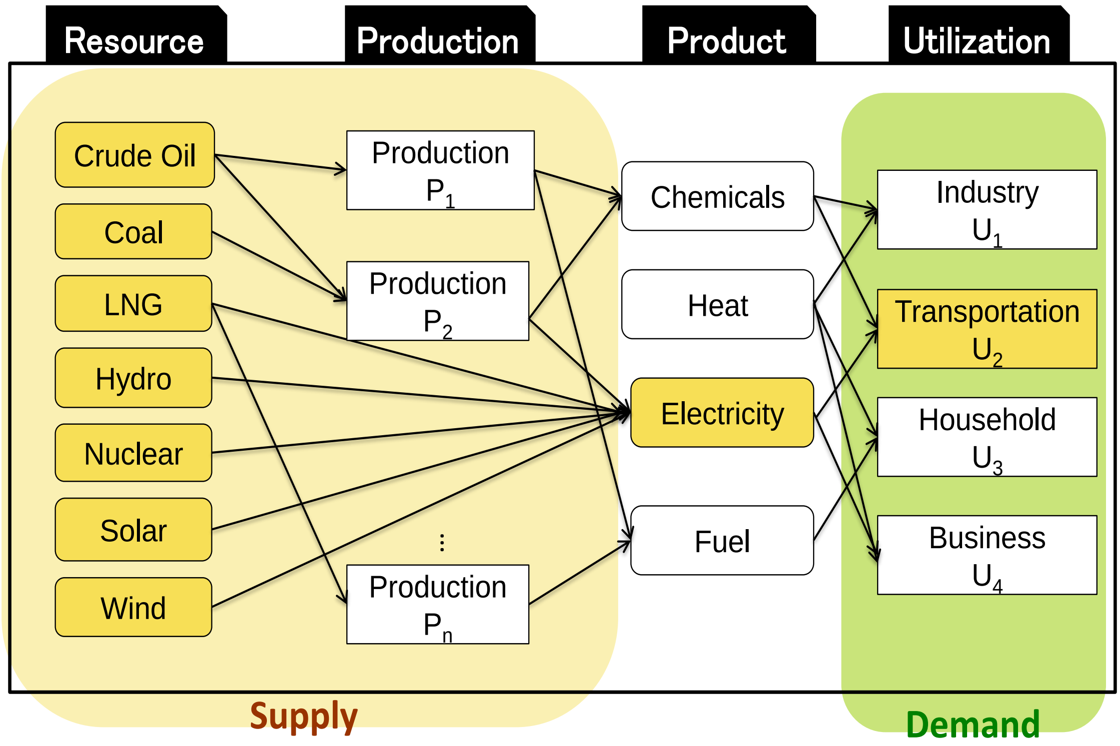


Figure 4-7 System boundary of the case study of Japanese energy system

4.3.3 Calculate environmental impact of selected technologies and their potential

According to the technology forecast made and introduction target set by the Japanese government (MOE, 2013), electricity generated from renewable energy, such as solar PVs and wind turbines, will be introduced aggressively in the future. Since the operation of nuclear power plants is facing political uncertainty, a scenario assessing the situation of an energy system without operating nuclear power in year 2050 is analyzed. Maximum potential power generation in years 2010 and 2050 is calculated accordingly, as summarized in **Table 4-3**. Environmental impacts (i.e. GHG emission) of each power generation technology from cradle-to-gate (Fukushima et al., 2004; Imamura et al., 2010) are calculated. In production technologies, the highest environmental impact induced by the production process is by coal, whereas the lowest environmental impact is by hydropower, as shown in **Table 4-3**.

At the same time, energy-saving technologies in the utilization subdomain, such as next-generation automobiles, show high potential to be introduced (METI, 2010b). In the case study, several innovative mobiles are assessed to solve the problem of fossil fuel dependence and GHG emissions from fuel combustion (Kato et al., 2010).

Table 4-3 Inventory results of subdomain technologies (Imamura et al., 2010; Kato et al., 2010)

	Technology	GHG emission ($g-CO_2/kWh$)	Y2010 generation (GWh)	Y2050 generation (GWh)
Production	Nuclear	20	460,671	0
	Coal	943	341,948	6,312
	LNG	590	341,948	0
	Oil	738	276,591	0
	GCC	474	253,724	419,850
	Hydropower	11	181,456	181,456
	Geothermal	13	4,581	45,408
	PV	38	5,321	204,657
	WT	25	4,617	122,650
Utilization	BAU	0	963,084	628,628
	EV_gasoline car replacement	–434	0	31,977
	EV_diesel car replacement	–395	0	12,323
	EV_LPG car replacement	–383	0	63,524
	PHV	–442	0	25,348

4.3.4 Generate graphical representations

The results shown in **Table 4-3** are used to generate a graphical representation of technology combination and production subdomain **Figure 4-8**. **Figure 4-8** shows the power supply (production) system of Japan in 2010. It indicates that there was a potential to generate about 1900 TWh of electricity, whereas demand was 986 TWh in that year. As shown in **Figure 4-8**, minimum and maximum environmental impacts induced by generating 986 TWh of electricity are visualized. It indicates all possible environmental impacts that are in between these two points. For example, the environmental impact of historical data (MOE, 2013) is in the middle.

Figure 4-9 is the result of a future scenario analysis that introduces PVs and WTs aggressively, together with utilizing energy-efficient fossil fuel technologies. It shows a great potential for GHG emission reductions by utilizing innovative technologies. **Figure 4-10** is the result of power demand (utilization) in 2050. Note that business-as-usual (BAU) in this case study stands for basic power demand without introducing innovative vehicles in the transportation sector. Decreasing power demand under BAU in year 2050 is due to the depopulation in Japan, and the implementation of high-efficiency technologies. Although the introduction of new vehicles will increase the power demand, it also contributes to the reduction of GHG emissions at the same time.

A comparison of I curves for 2010 and 2050 is shown in **Figure 4-11**. As illustrated, year 2010 has larger demand and higher GHG emission compared to year 2050. However, the length of I_{min}–I_{max} of 2010 is longer than that for 2050, which represents the higher operability in the system. It also addresses the risk in the 2050 scenario due to less operability of the electricity system. From the visualized result, a suggestion to redesign future electricity systems can be made by implementing more technologies in the production subsystem or by diminishing demand in the utilization subsystem to increase system operability. The visualized range of environmental consequence (P_{max}–P_{min}, U_{max}–U_{min}, and I_{max}–I_{min}) is changed under different scenarios as discussed in the above section. Although those results are shown for the target year, assessment of a long-term pathway is also possible. As shown in **Figure 4-12**, technology combinations in different years are visualized and comparable, which is especially important in designing long-term energy policies to assess the effects of constraints changed in technology implementation over time.

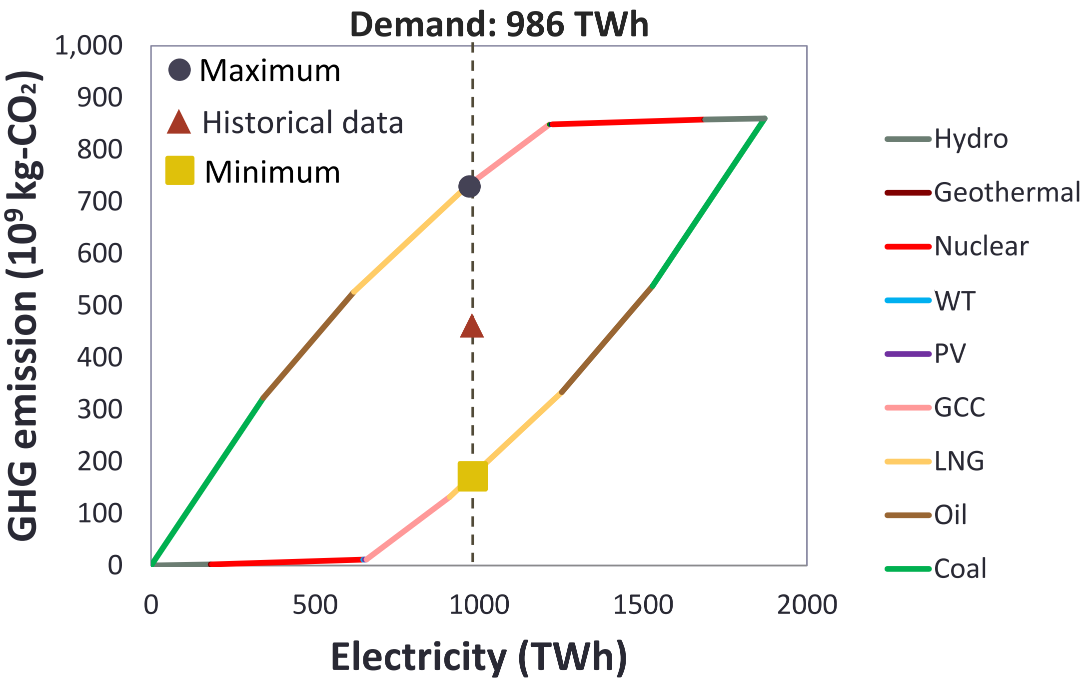


Figure 4-8 Graphical representation of power supply in Japan in year 2010 (P curves)

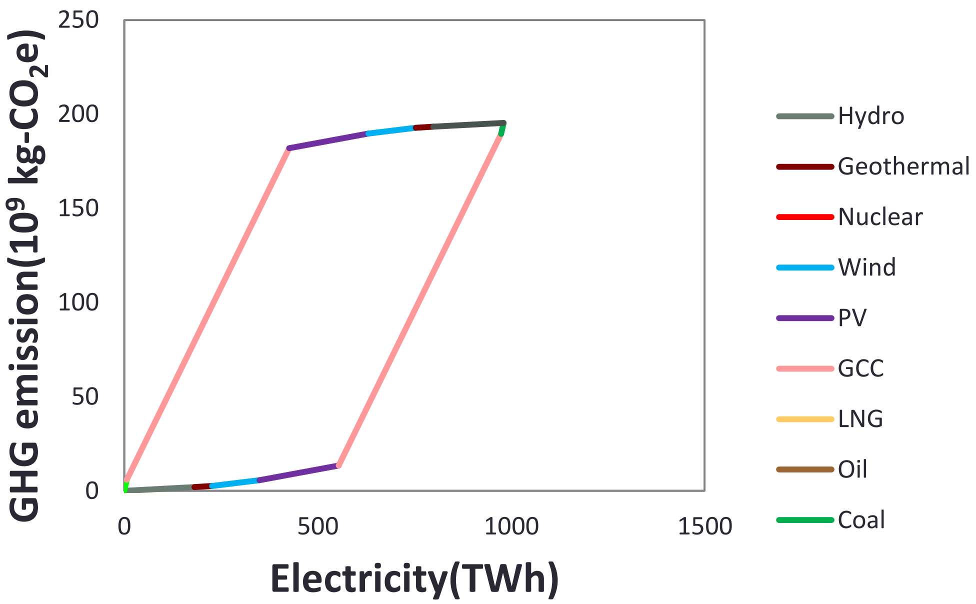


Figure 4-9 Graphical representation of power supply in Japan in year 2050 (P curves)

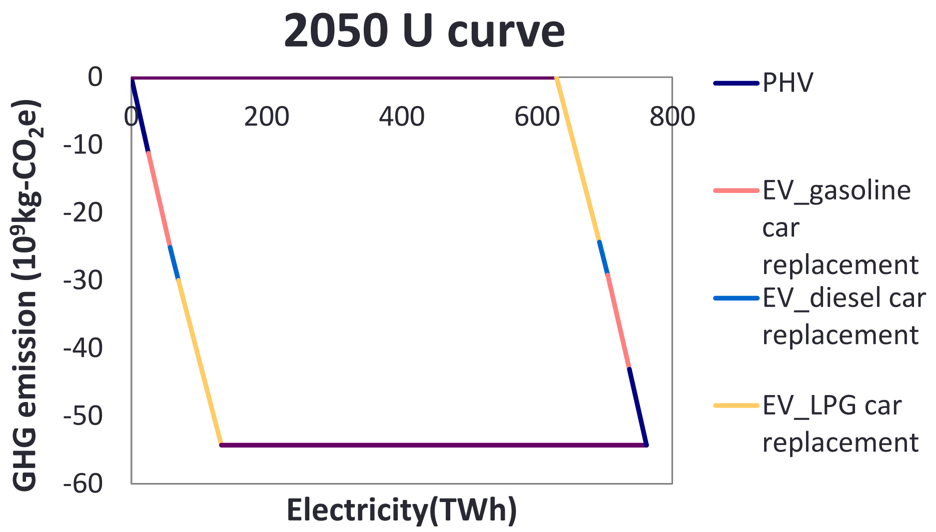


Figure 4-10 Graphical representation of power demand in Japan in year 2050 (U curves)

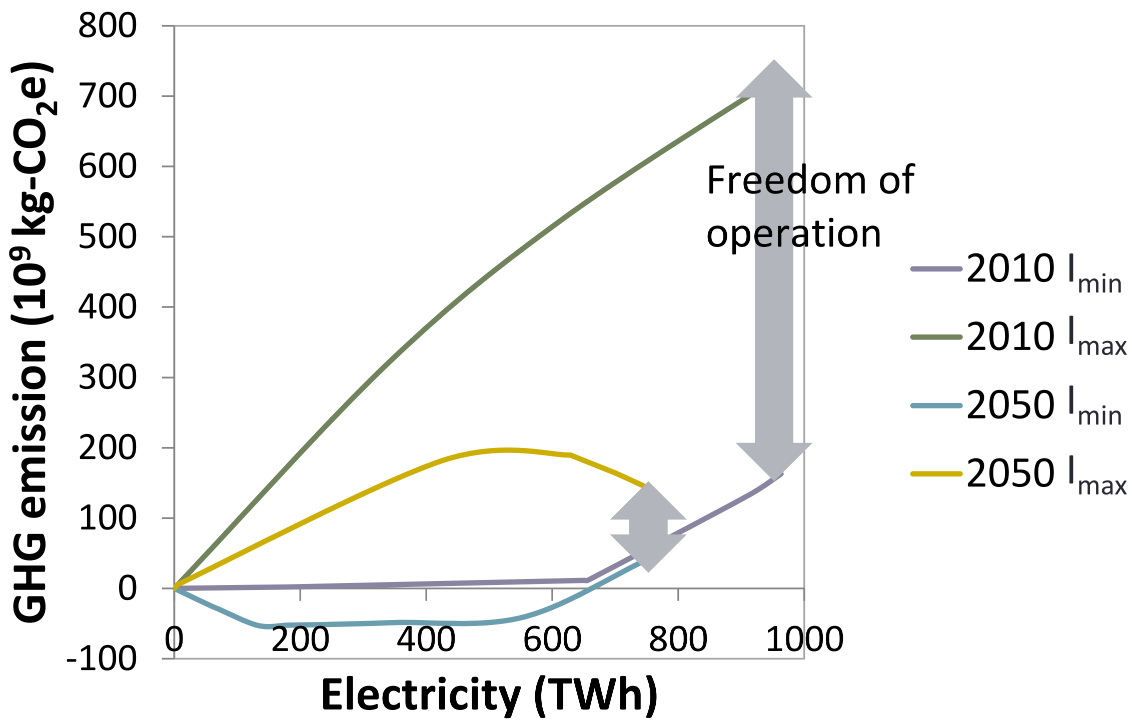


Figure 4-11 Comparison of graphical representation of the energy system between years 2010 and 2050

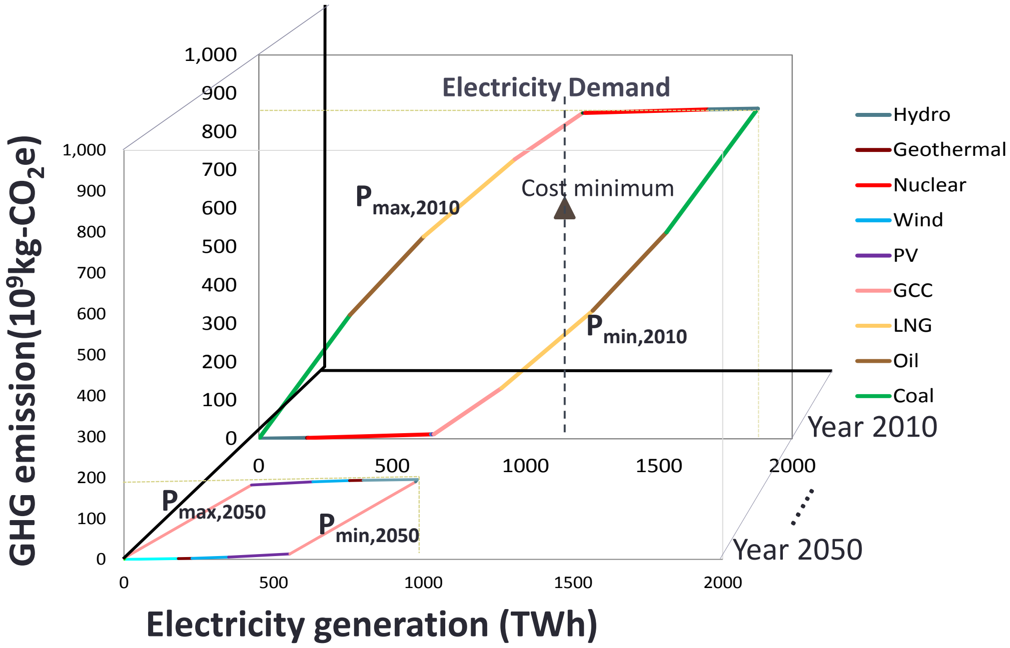


Figure 4-12 Visualization of electricity generation with time frame

This framework provides a general approach for analyzing a system; however, the aspects to be considered will be different for each decision maker. For example, a system designer might pay more attention to scenario performance (e.g. cost, CO_2), but the plant operator would care more about the flexibility of a system. Therefore, it is necessary to identify who is the decision maker, as this is strongly related to the selection of evaluating indicators. **Figure 4-13** visualizes a situation of a power system without operating nuclear power in Japan. In the scenario of 0% nuclear power operation, the result shows that the mix of technologies is sufficient to satisfy the power demands and the requirements of a system designer. However, it also indicates that that plants have to run at almost full capacity and may not have enough maintenance periods, which increases the risk of operation. Scenarios 1 to 3 in **Table 4-4** with different operation conditions of fossil fuel-fired power plants are evaluated as shown in

Figure 4-13. It indicates that power supply is insufficient for demand under 50% operation rate of fossil fuel- fired plant, which is the average of the current situation. In this case, plant operators may argue the flexibility of this system. Furthermore, it is necessary to analyze system stability in terms of instantaneous power generation, especially weather-dependent power generators such as PVs and WTs.

Table 4-4 Settings in evaluated scenarios

Reference	Scenario 1	Scenario 2	Scenario 3
100% operation of all plants	0% nuclear	0% nuclear + fossil fuel-fired with 50% operation	0% nuclear + fossil fuel-fired with 80% operation

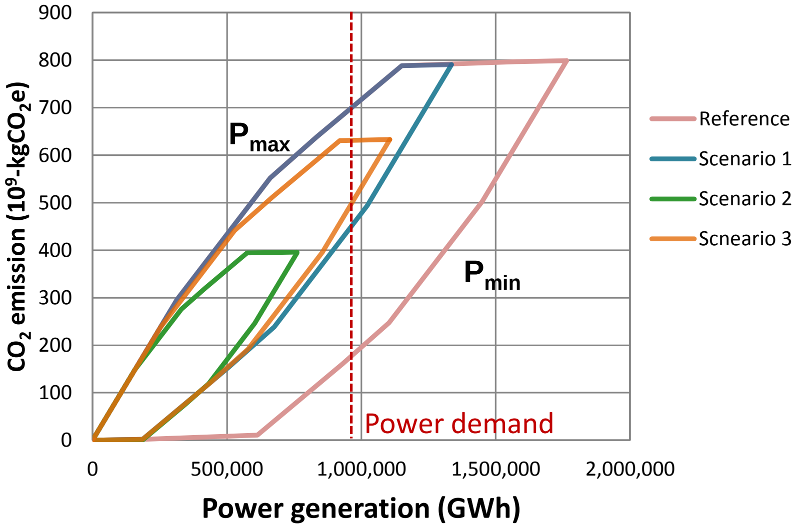


Figure 4-13 Comparison of scenarios with defined operation conditions (Power generation basis)

On the other hand, from the environmental perspective, the current energy system is superior to the contribution in GHG emission and has large emission allowance in the power system. (i.e. longer distance between P_{max} and P_{min} cut by vertical demand line). The comparison of possible emission among different scenarios is clarified by the visualization method.

A safe energy system is not only a system that can provide sufficient electricity amount for demand, but also sufficiently supply in peak demand without system breakdown. As discussed, the “no nuclear power option” is sufficient in terms of electricity demand (GWh), but it is insufficient in the peak demand hour as shown in **Figure 4-14**. Although an insufficient amount can be made up by other storage facilities (ex. hydro-pump, battery and so on), it is still seen as a fragile system.

Therefore, for designing a stable future energy system, system security is an essential issue. The future Japanese society is supposed to shift to a renewables-based society, and population will decrease according to the estimations by the government. Therefore, a set of mid-term and long-term future scenarios is assessed by the visualization method. **Figure 4-15** shows a scenario in year 2020, which is a no nuclear power society with the introduction of solar photovoltaic (PV) panels. Since power generation efficiency of PV is highly depend on the weather condition, the fluctuation of power generation should be taken into consideration. **Figure 4-16** illustrates fluctuations in PVs, showing that the system can meet peak demand even on rainy days (supposing PV efficiency is 0). However, it is showed that the smaller the efficiency, the less operable the system becomes in this case.

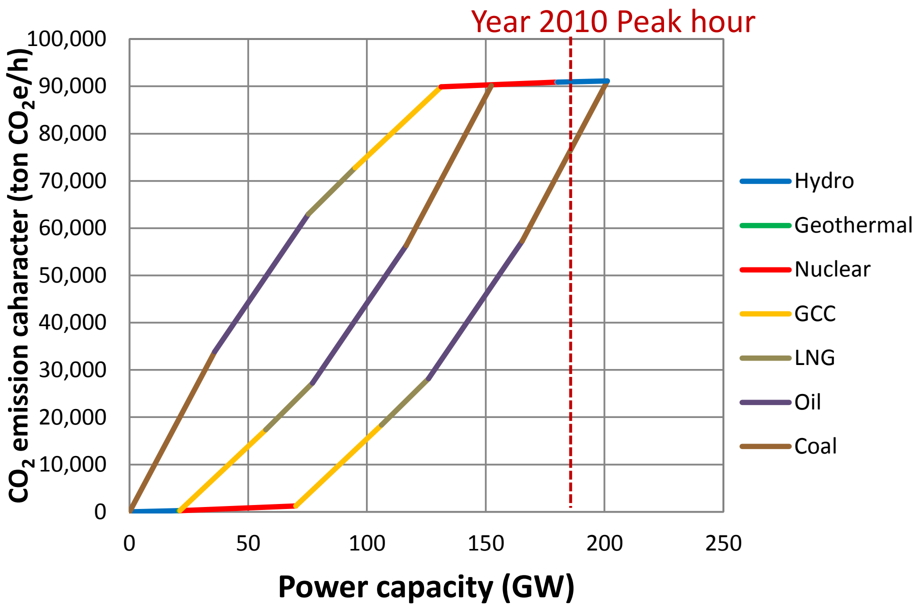


Figure 4-14 Visualization of reference and no nuclear power scenarios (Power capacity basis)

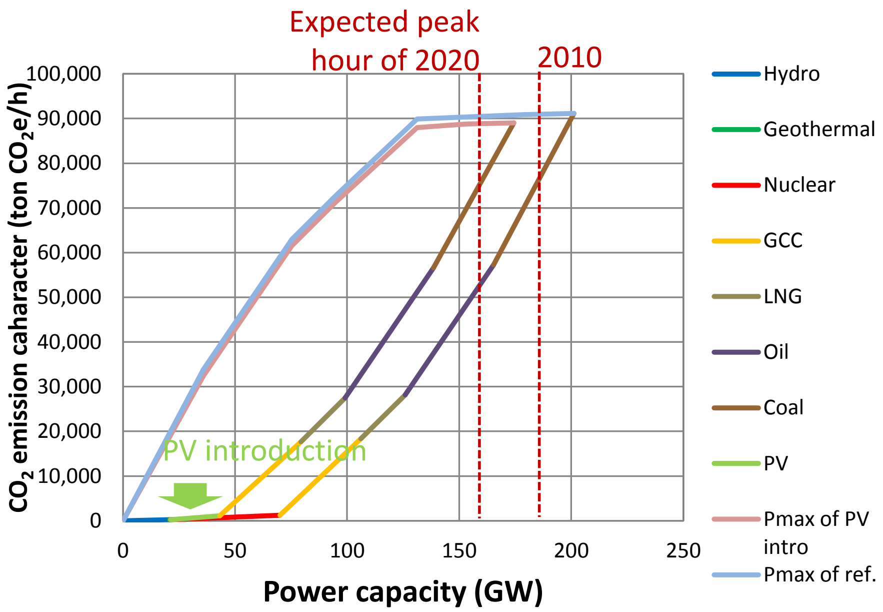


Figure 4-15 Visualization of PV introduction without nuclear option (Power capacity basis)

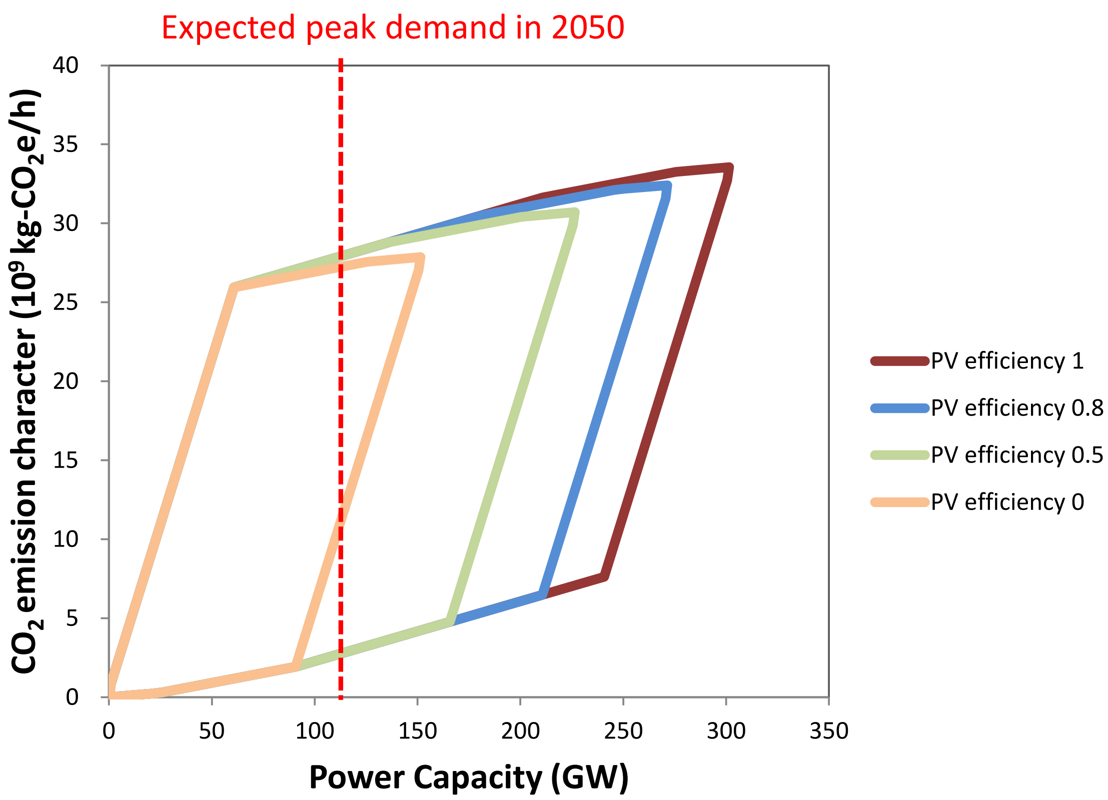


Figure 4-16 Visualization of PV fluctuations (Power capacity basis)

4.3.5 Cost optimization of power mix

Instead of only showing the range of consequence of technology implementation, optimization model is integrated to provide the cost information in the visualization model. This is to analyze and evaluate tradeoffs between technologies, policies, and cost for mitigation of environmental problems.

The objective function here is minimizing total power generation cost of centralized power generation system from year 2010 to 2050, which is shown as follows:

$$\mathrm{TC} = \mathrm{TC}_0 + \sum_{k=1}^{n} g_k \times InvC_k \times Cap_k) + \sum_{k=1}^{n} (FuelC_k \times Pow_k) \qquad \textbf{Equation 4-5}$$

Where TC = Total cost per year (¥/yr)

TC_0= Total cost of hydropower and geothermal in Japan per year (¥/yr)

k = type of power source (i.e. NUCLEAR, COAL, LNG, OIL, GCC…)

g = annual expense ratio (1/yr)

InvC = investment cost (¥/kW)

Cap = installed capacity (kW)

FuelC = fuel cost of electricity power generation (¥k/Wh)

Pow = amount of power generated electric power in a year (kWh/yr)

$$g = \frac{1-r}{N} + I + f + m - \frac{1-r}{N}(I+f)\left(\frac{1}{I} - \frac{N}{(1+I)^N - 1}\right) \qquad \textbf{Equation 4-6}$$

Where

r= residual value (dimensionless)

N = depreciation period (yr)

I = interest rate (1/yr)

f = property tax (1/yr)

m = ratio of running expense (1/yr)

Constraints:

There are several constraints in the optimization model in the following. In general, the supply and demand of the electric power is balanced by **Equation 4-7** for particular time *t* and day *d* of a certain regain *j*. The electric power that a certain power source can generate is restricted by the installed capacity, Cap_i, of the power source. An inspection ratio, u_i, which reduces the output power due to the periodic inspection for each power source is described in **Equation 4-8**.

$$\sum_{p=1}^{n}\sum_{q=1}^{10} X_{p,q,t,d} - S_{q,t,d} + Hydro + Geothermal = Load_{q,t,d}$$ **Equation 4-7**

$$X_{p,q,t,d} \leq (1-u_p)\times Cap_p$$ **Equation 4-8**

Where

p = type of power source

q = power company

t = hour of the day

d = day of the year

X = electric power generated per unit time (kWh/kw)

S= electric power stored by pumped storage power generation per unit time (kWh/kw)

u = inspection ratio (dimensionless)

The installed capacities for each power source are constrained by both lower and upper limits as giving in **Equation 4-9** and **10**.

$$Cap_{p,q} \geq Cap_{L,p.q}$$ **Equation 4-9**

$$Cap_{p,q} \leq Cap_{U,p,q}$$ **Equation 4-10**

The storage and capacity balance of hydro-pumped are expressed by **Equation 4-11** and **12**, respectively for a given day *d*.

$$H \times \sum_{t=0}^{23} X_{pump,q,t,d} = Eff_{storage} \times H \times \sum_{t=0}^{23} S_{q,t,d}$$ **Equation 4-11**

$$H \times \sum_{t=0}^{23} S_{q,t,d} \le M_{storage} \times (1 - u_{pump}) \times Cap_{pump}$$ **Equation 4-12**

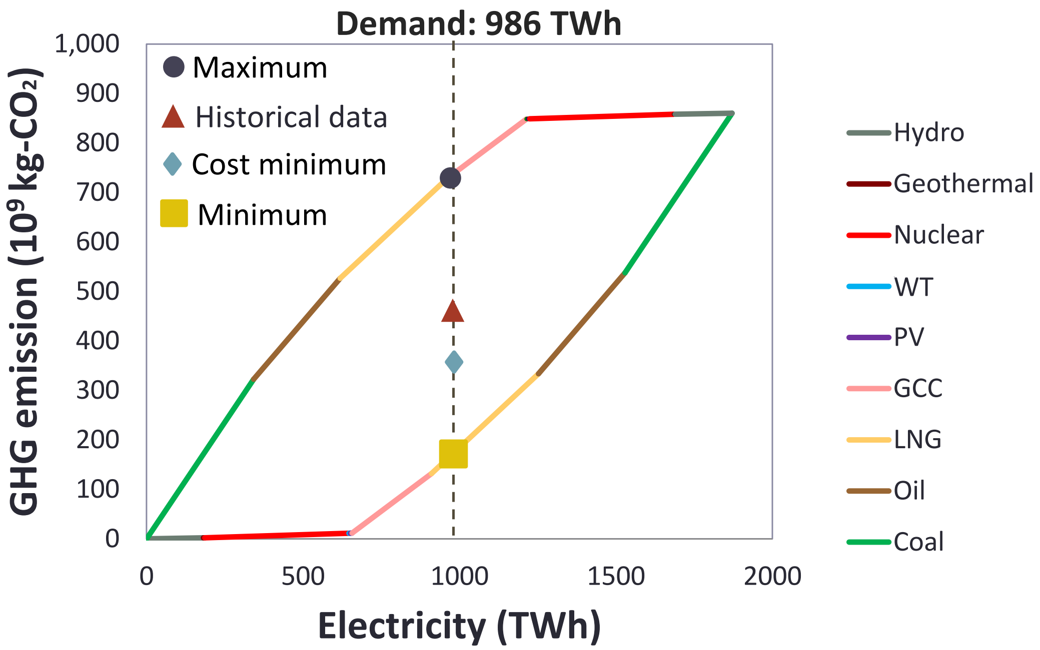
Where

$Eff_{storage}$ = efficiency of pumped storage power generation (dimensionless)

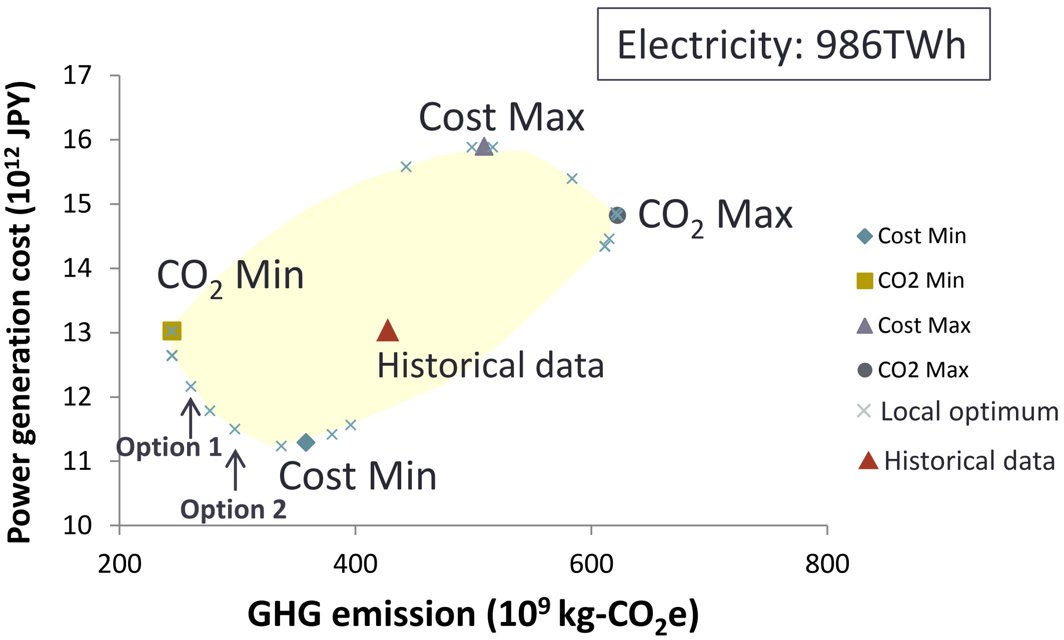
$M_{storage}$ = pumped storage power generation capacity (kWh/kw)

4.3.6 Visualized relation of environment and economy in electricity system

The proposed method can also be used to visualize results of economic optimization, showing potential environmental impact compared with those of other choices of technology combinations under the same capacity standard. For example, **Figure 4-17** (b) shows the relationship between cost and CO_2 emissions when generating 986 TWh of electricity. Historical data is closer to the region of LM (less cost and more CO_2) as illustrated in **Figure 4-17** (b). The cost distinction between historical data and CO_2 minimum is not remarkable; however, CO_2 emission is higher than the cost minimum point. It shows the potential for improvement in the Japanese electricity system to achieve lower emissions by changing technology implementation and operation. This kind of visualization can help decision makers to compare several operation conditions at one time, while showing the attainable region of different technology implementations.



(a) Relation of electricity generation and GHG emission



(b) Relation of GHG emission and cost

Figure 4-17 Relations of power generation cost and GHG emission when 986TWh is supplied

The proposed graphical representation method shows its applicability in supporting the design of mixed power generation strategies. For example, **Figure 4-18** shows technology combinations under the different operation conditions given in **Figure 4-17** (b). In the context of cost minimization, power generation from coal has a higher ratio than other fossil fuels, while LNG-fueled plants have the advantage of minimizing CO_2 emission, which also needs to be considered. Nuclear power plants have similar ratios in both cases. The composition of the technology mix in the other two options is also shown in **Figure 4-18**. **Table 4-5** makes a comparison of cost minima for the two options, and reveals that increasing 4% of the cost can contribute to a 23% reduction in CO_2 emissions (option 1). In contrast, a 10% increase in cost only contributes to a 30% reduction in CO_2 emissions (option 2). From the point of view of cost effectiveness, option 1 is recommended.

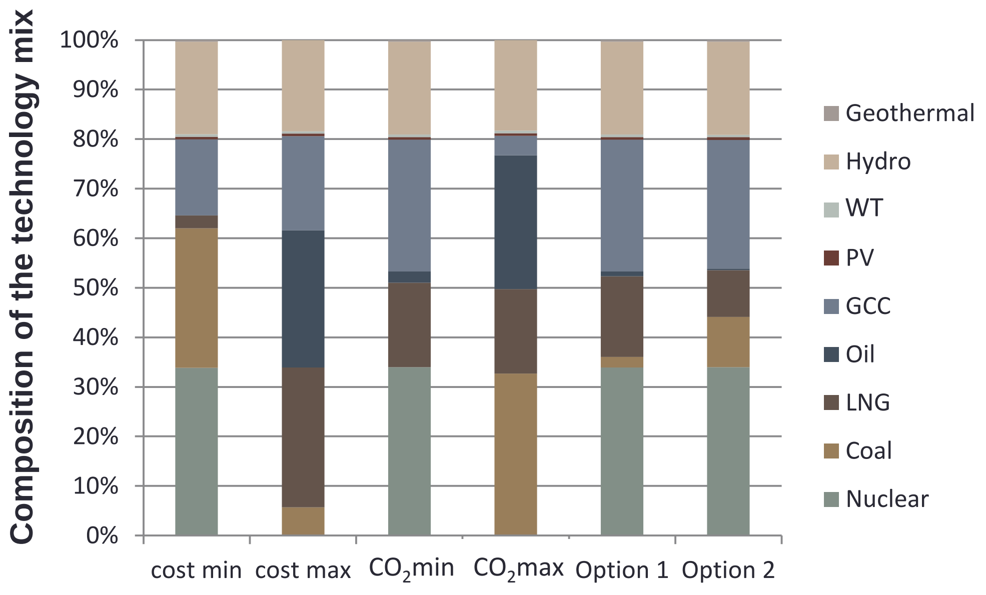


Figure 4-18 Fractions of technology combinations under specific conditions

Table 4-5 Comparison of cost and CO_2 emission within alternative options

	Cost Min	Option 1	Option 2
$CO_2/CO_{2\_cost\ min}$	1	–22.70%	–30.20%
$Cost/Cost_{\_cost\ min}$	1	4.40%	10.50%

To provide decision makers with the cost information for the whole system, **Figure 4-19** shows the cost minimization profile for power generation. In this figure, three regions are distinguished because of technology characteristics within the system operation. Cost minimization points shown in region II of the figure indicate the lowest power generation cost for each generation amount. In region I, hydropower is set as the base load of a system that operates continuously over the year, and the power demand is less than the capacity of hydropower generation. Hence, all supply will be provided by hydropower. In region III, total annual demand is sufficient but there are certain days in a year where the supply cannot cover the peak time demand. Thus, economic optima were not identified. Therefore, even total power generation is essential for the system, while detailed technology operation should be considered at the same time to ensure the security of the system.

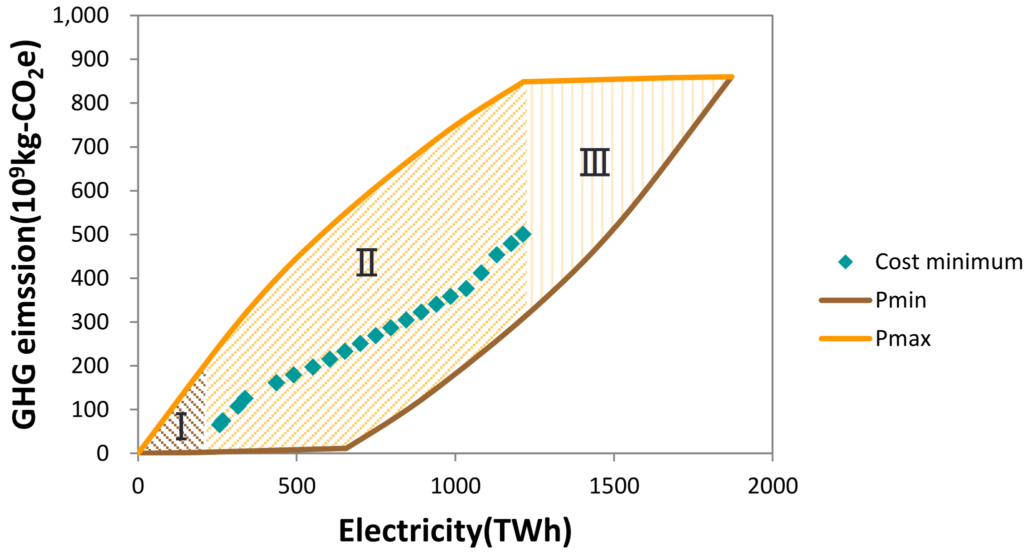


Figure 4-19 Cost minimization profile and three regions of technology operations in the energy system

4.4 Summary

In Chapter 4, two case studies are presented for demonstrating the proposed graphical representation method: hydrogen-related technology in Taiwan and electricity-based system in Japan. The former one is to assess a grassroots design (i.e. a new system) while the latter is discussing different technology implementation in a retrofit design (i.e. an exist system).

The case studies highlight the applicability of the visualized scenario analysis method in complicated energy systems. The applicability of this methodology is demonstrated by case studies discussing scenario performances and behaviors by implementing various power generation technologies in the Japanese electricity system.

Based on similar analyses, future technology combinations can be designed according to the required constraints. Decision makers can use this practical approach to identify key policy issues. The main benefit of this visualization approach is the capability to express scenario performance and behaviors systematically. Such analyses directly provide visual comparisons with multiple indices, ensuring that decisions can be made with confidence when designing new systems because all consequences are comparable. If the evaluated scenario does not achieve the required goal, decision makers can go back to the first step of the framework with strategic information (i.e. relationship between cost and CO_2 emission in this case study) by knowing the potential of the system.

CHAPTER 5 METHODOLOGICAL FRAMEWORK FOR TECHNOLOGICAL DECISION MAKING

5.1 Introduction

In recent years, there have been many concerns in public sectors to make effective strategies. It is pointed out that one of the most important tasks during strategy making is the management of the interfaces between different and often competingstakeholders in relation to their strategic goals (Ackermann & Eden, 2011). The importance of stakeholder management and corporation is also the case in making strategies in introducing and diffusing energy technologies. For example, feed-in tariffs scheme（FITs) is known as an approach to foster renewable energy via economic incitement. Because electric utilities will be obligated to purchase electricity generated from renewable energy sources such as solar PV and wind power on a fixed-period contract at a fixed price, which will promote the introduction of renewable energy. Under this scheme, the relationship and interactions among stakeholders such as electricity customers, energy enterprises, local and national governments will lead to various issues. Some researchers have suggested that distinguishing existing stakeholders with relevant factors by managed knowledge is possible to influence the future energy policy (Matsuura, Shiroyama, & Suzuki, 2008; Tanaka, 2011).

However, the complexity of energy system increases the difficulty in making decisions. A policy maker has the bird-eye view to generate a national-level policy, but he or she may not be familiar with the progress of novel technologies and the evaluation of them. On the other hand, a researcher or a technology developer standing on a scientific field may not notice the potential of their contribution to society. Any stakeholder alone cannot realize a sustainable energy system.

Since the perspectives from different stakeholders are varied, the structured knowledge and management within the decision-making process will significantly contribute to generating the consensus. In the previous chapters, novel graphical representation methods for strategic decision-making were proposed and demonstrated their applications by case studies. The method is providing a top-down viewpoint for the policy making without detailed analysis among corresponding stakeholders. It is believed that logical description of the decision-making process with actual procedures and data requirements will greatly facilitate the strategic generation of policies.

Therefore, for the practical implementation of technological decision-making, this chapter presents an operational representation of the design framework that analyzes the activities of different stakeholders. The relations among stakeholders, policy makers, researchers, practitioners, and technology developers in a decision-making process are identified by using the activity modeling. A standardized activity modeling method, type-zero method of Integrated Definition Language (IDEF0) is applied (Ross, 1985; NIST, 1993) to hierarchically clarify exact activities with information flows in executing the process of strategic decision making. The proposed activity model can be used as a foundation to incorporate management, assessment, and development under hierarchical basis.

5.2 Relations among stakeholders in decision-making

When several persons or organizations are involved in decision-making, mutual dependencies and the distribution of power or authority among the participants become important dimensions that characterize the process.

When actors of technological policy making presented in **Figure 5-1** are considered, three different aspects can be identified accordingly. **Figure 5-1** shows a schematic of information flows among actors (practitioner and stakeholders) in the evaluated energy system. For the policy makers in energy sectors, how to manage and implement technologies is the biggest concern. For example, if a policy maker is going to promote a strategy for a low-carbon society, he or she might have the GHG emission reduction target in mind but without enough technological information. In such case, policy makers can provide information on the candidate technologies to the practitioner (i.e. researchers and experts of technology assessment and evaluation) conducting the analysis. Practitioners receive the request from the policy maker and execute the project by some evaluation methods (e.g. LCA, risk assessment, cost evaluation, or graphical representation proposed in this study). After the analyses, the information for decision-making (i.e. evaluated results) will be provided again to policy makers to generate a more strategic policy such as making priorities of technology implementation in the energy roadmap.

On the other hand, the information flow between policy makers and technology developers also exists. For example, an environmental-friendly technology can be proposed by a technology developer to apply for subsidies (or investment) from the government. With the support of 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 feedstock yield (extend respective segment of P curve in horizontal direction), and reduction of energy consumption in the production process (reduction in the gradient of the respective segment of the P curve, i.e. **Figure 4-5**).

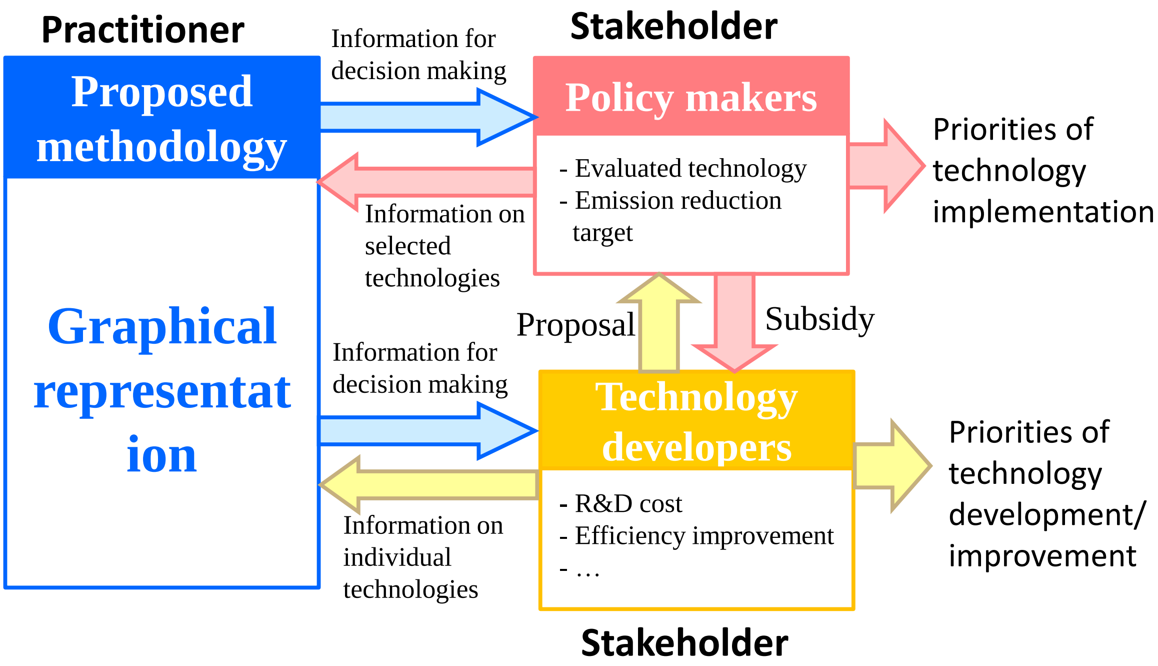


Figure 5-1 Information flows and characteristics/interactions among actors

There is a variety of technical actions that can be implemented for reduction in GHG emissions and for mitigation of climate changes as well. The energy use is influenced by many different technologies, processes and products under different types of constraints. Decision directions, which need to be analyzed systematically, are connected to these exogenous and endogenous constraints, such as energy prices, political issues, economic and business situations, and managerial priorities.

Policy makers may not have all required knowledge in the decision making process which should be supported by other stakeholders such as researchers and technology developers. Therefore, a platform for technological communication is necessary for generating consensus among stakeholders.

In order to propose the practical framework, procedures of the decision-making process across different stakeholders conceptually described in Figure 5-1 are clarified in more detail by an activity modeling method. To enable practical decision-makings, the relationship among activities, tools, mechanisms and information flows are illustrated using IDEF0 activity modeling method in next section. For instance, several researchers have applied this activity modeling approach to integrate new or existing engineering methods and tools for environmental protection in process design (Fuchino & Shimada, 2003; Fuchino, Wada, & Hirao, 2004; Sugiyama, Hirao, Fischer, & Hungerbühler, 2008; Kikuchi & Hirao, 2009).

The objective of this hierarchical description is to clarify the process of developing technology introduction, including tools, resources, evaluation methods (e.g. visualization method) and knowledge accumulation described in this thesis.

5.3 Illustration of method under IDEF0 representation

5.3.1 IDEF0: Activity modeling technique

Type-zero method of Integration of Definition for Function (IDEF0) is an activity modeling (Ross, 1985; NIST, 1993), which offers a functional modeling language for analysis, development, and has been widely used in business process reengineering (Systems Engineering Fundamentals, 2001).

IDEF0 is originated from a structured analysis and design technique (SADT), a software engineering technique for describing systems as a hierarchy of functions. An IDEF0 model is composed of a series of graphical diagrams and texts. In IDEF0, all administrative and operation procedures are broken down into activities, and systemic relationships among them are described as the input, output, control, and mechanism as shown in **Figure 5-2**. The box represents a function or an activity, which has a verb as a name. The input arrows, entering the activity box from the left side, represent the objects (e.g. information, requirement…etc.) that are transformed by the function into the output arrows on the right side. Arrows entering the box on the top represents the control or constraint of the activity. The mechanism arrows on the bottom are information, resources, and tools for the activity.

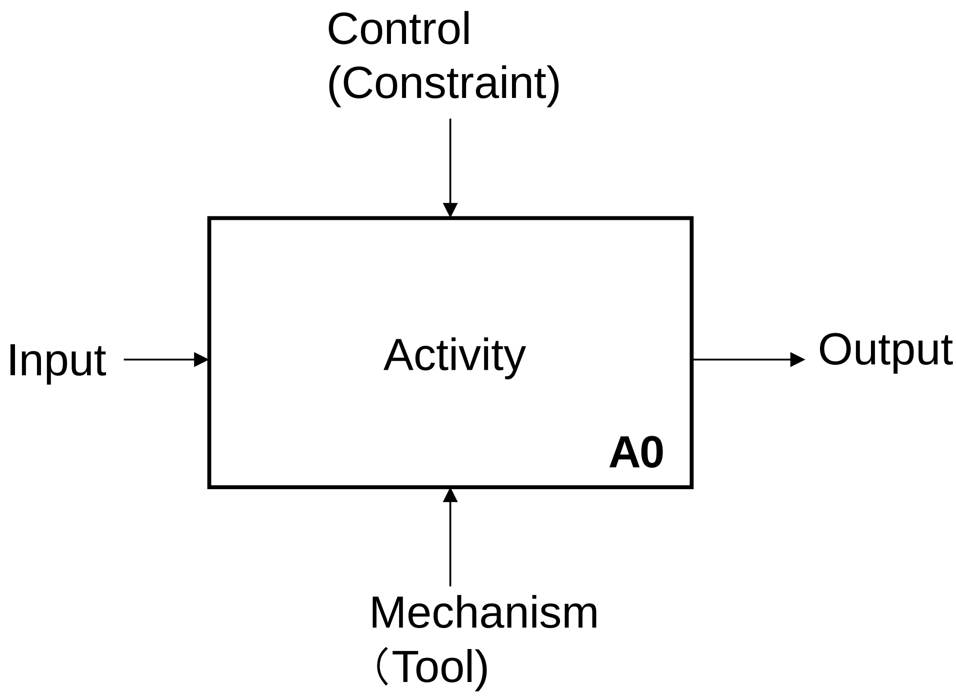


Figure 5-2 Syntax and semantics of an IDEF0 model

Each model has a single top-level activity named A0. The top activity A0 can be hierarchically decomposed into sub-activities models A1-Am (n=2, 3, …, m; m∈N) that have the same boundary as the parent activity (i.e. A0), as shown in **Figure 5-3** (m=3). In the same way, each of the activities (A1…Am) can be further decomposed into sub-activities (A11, …, Amn; n∈N) if needed. As shown in **Figure 5-3**, the input, output, control and mechanism of the top-level A0 must be the same of the decomposed sub-activities A1 to A3 (i.e. they have the same boundary as the parent activity A0). The interaction among the sub-activities can be described as well. This approach is possible and particularly useful to describe complex activities in detail, which helps executers to have an overview of the entire activity.

The activities illustrated in an IDEF0 model need a viewpoint and objective. The viewpoint represents what perspective the model is developed, and specifies the actors of the activities. The activities within a model can be carried out by multiple people, but they should have the same viewpoint.

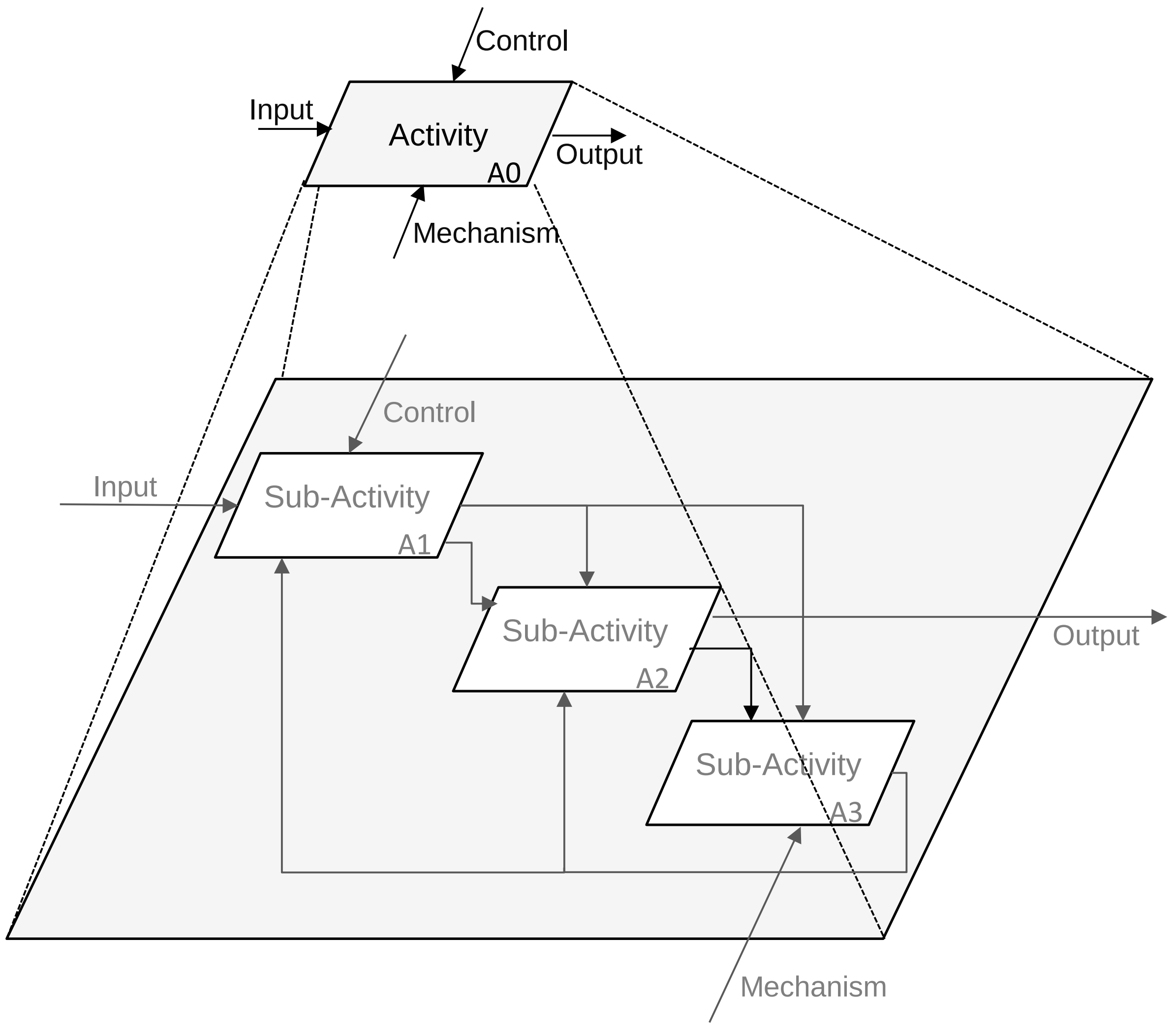


Figure 5-3 Expansion of top-activity A0 to sub-activities

5.3.2 Framework represented by activity modeling

In order to develop the practical framework for technology introduction strategies that describe concrete procedure with corresponding actors, three IDEF0 models with different viewpoints are presented here. **Figure 5-4** shows the overview of the entire activity, which contains different actors in this practical framework. In this framework, the collaboration and relationship among three types of stakeholders in generating new technology strategies are described by the flows of information among the three IDEF0 models.

Three types of stakeholders (S1, S2, S3) engaged in the project of designing technology introduction strategy are defined as policy makers, researchers and practitioners, and technology developers. Within this framework, the objective of S1 (i.e. policy makers of the government) is to manage projects on developing technology introduction that will be more focused on in this thesis. The objective of S2 (i.e. researchers, practitioners) and S3 (i.e. technology developers) are "develop mechanism for technology & system evaluation" and "Research & Develop innovative technologies", respectively. People that are categorized as S2 are the ones those who develop evaluation methodologies (e.g. LCA, risk assessment), practitioners, or system researchers in either academic field or research institutes. Members grouped under S3 category are who do fundamental research for developing innovative technologies and/or make it into practical applications in academic field, research institutes, and companies.

As shown in **Figure 5-4**, there are many information flows among each other. The outputs from S1 are provided as inputs and controls for S2 and S3. That is, the future directions/visions that are the outputs of S1 will directly or indirectly influence other stakeholders in relation to the distribution of research grants or subsidy giving that are seen as the controls of S2 and S3. S1 is also possible to inquire for innovative technologies or technology evaluations by its authority. On the other hand, the outputs of S2 and S3 can serve as feedback information as controls and mechanisms of S1. For example, the research outputs (e.g. simulation models, evaluation methods, scientific accomplishment, technical information, etc.) from S2 and S3 can become the tools and supporting information to develop advanced technology introduction strategies.

In this thesis, the S1 model is focused so that the detailed information flows connected with S1 are shown as black arrows and the decomposed activity model of S1 will be described in the following. The other information flows described in gray (i.e. inputs, controls, mechanisms to S2 and S3; outputs from S2 and S3) will not be further explained in this thesis but can be analyzed by the similar approach of S1.

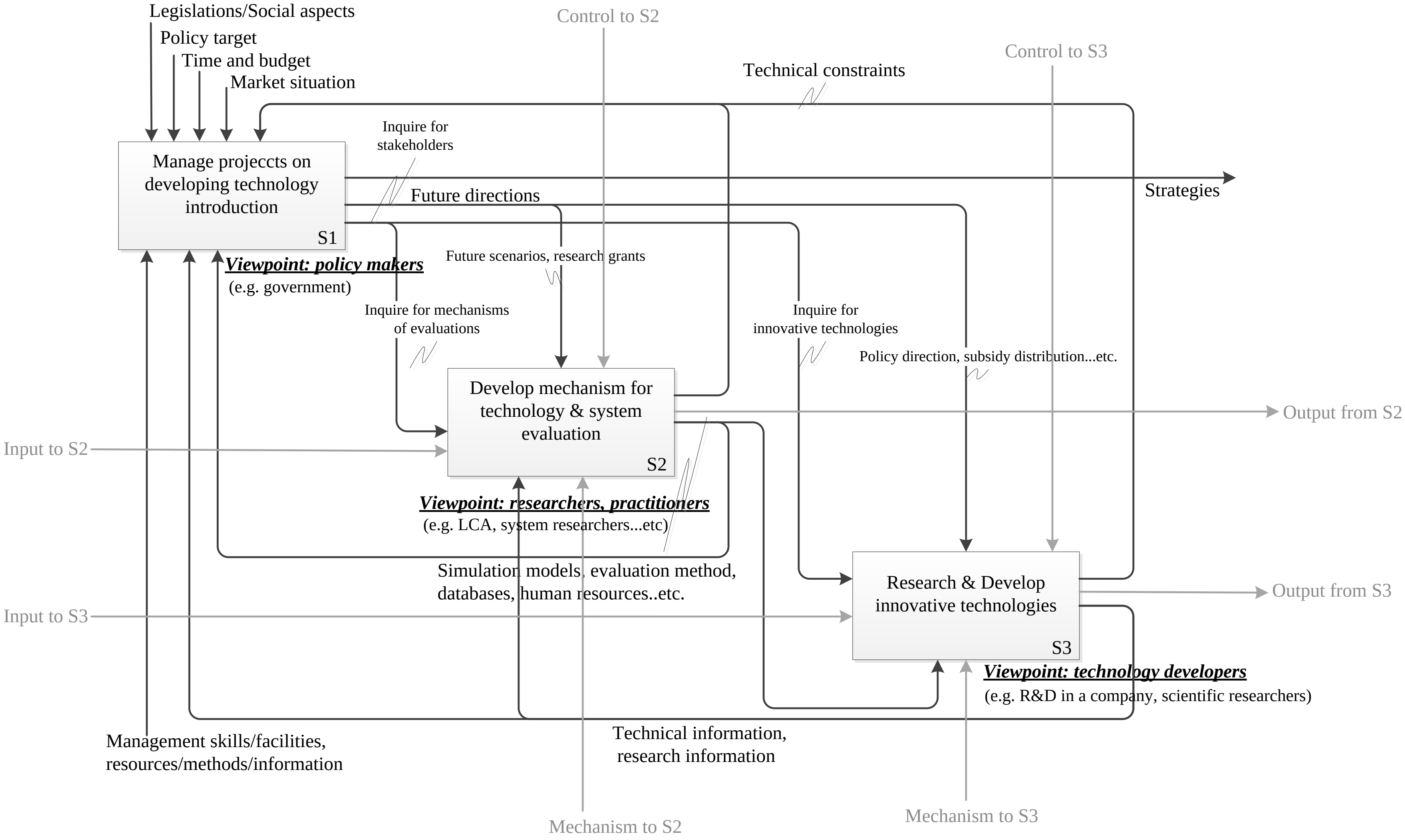


Figure 5-4 Cooperation and relationship among three stakeholders in generating new technology strategies

Figure 5-5 shows the top-activity S1-A0: Make strategic technology introduction decisions. Several constraints and giving resource/mechanism are needed for executing this activity. The viewpoint of this model is a decision maker who designs policies and develops technology introduction strategies. The one who executes this model may be on national (e.g. Committee on the Cabinet) or regional levels (e.g. officers in local government). "Legislations/social aspects," "market situation" are exogenous constraints, whereas "policy target," "time and budget" and other general constraints are endogenous ones. For example, shutting down all of the nuclear power plants in Japan temporarily is reflecting the public opinion that is seen as an exogenous factor.

On the side of the mechanism, "simulation model," "existing databases," "knowledge and know-how," "simulation models," "management skills/facilities," and "human resources" are defined here. The overall outputs "strategies," "accumulated knowledge," "request for mechanism of evaluations/innovative technologies" are produced after executing this activity.

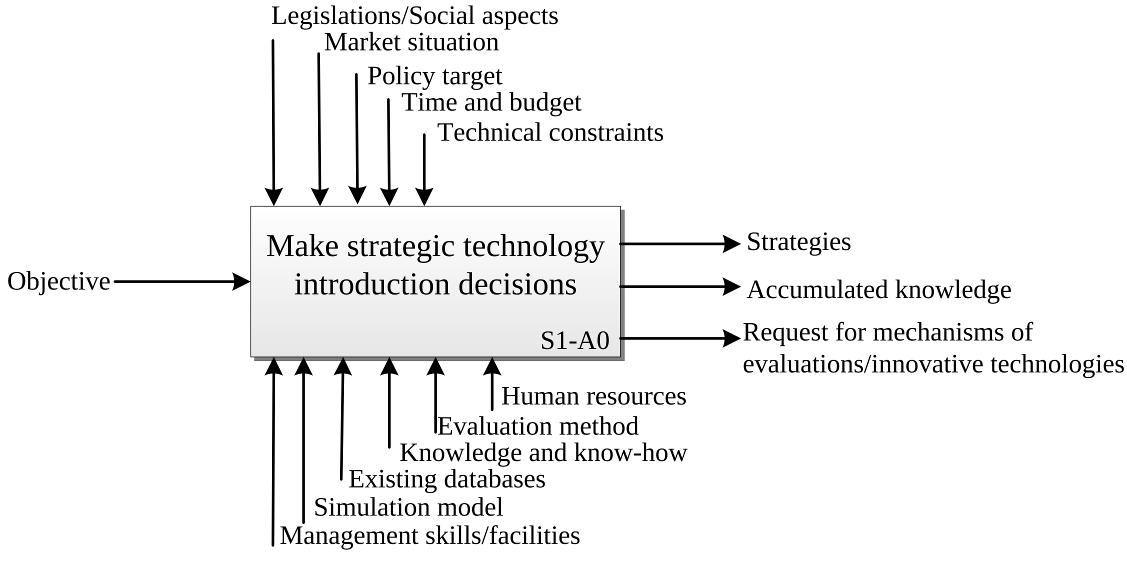


Figure 5-5 Top-activity S1-A0: Make strategic technology introduction decisions

S1-A0 then can be decomposed into S1-A1 to A7, as shown in **Figure 5-6**. A1 is an activity that manages technology introduction decisions. The administrator of this activity may be one person (e.g. the Cabinet) or a group of people (e.g. Committee on the Cabinet). The objective is the input of this activity, which is together with a lot of controls/constraints and mechanisms. One of the outputs from A1 activity is to inquire for generating scenarios in A2 and A4 activities, and the other is to convert into internal constraints of the whole activities as well. A2 and A3 are the activities to generate a baseline scenario and do the evaluation. In a retrofit design of an exist system, the current status needs to be confirmed and evaluated for generating the alternative future scenarios. In the case studies presented in Chapter 4, it is only valid in the second case study (i.e. electricity system). The output of S2 is the generated scenario that becomes the input of A3 and at the same time the feedback to A1 as a control.

A4 and A5 are the activities to generate alternative scenarios and do their evaluations. Both grassroots and retrofit designs (i.e. case studies of hydrogen and electricity systems in Chapter 4) must have these activities. The decomposition of the activities will be presented as follows. Since the procedures of A2 and A3 are similar to A4 and A5, respectively, only A4 and A5 are further decomposed.

Figure 5-7 represents the sub-activities of A1: activities A11-A14. As shown in this figure, there are four sub-activities: manage S1-A1-level activities, decide a decision scope, select technologies in the boundary, and provide preliminary decision target. In A12 activity, objective is the input and decided scope is the output under several controls and mechanisms. For example, the government tries to design a sustainable energy system by introducing hydrogen-related technologies, and the output of this sub-activity will be “hydrogen technology domain" (i.e. chapter 4.2.2).

Figure 5-8 describes the sub-activities A41 to A44: receive a request for generating scenarios; identify elements for generating scenarios; collect required data for generating scenarios; and generate scenarios for evaluation. The input to A41 is the output from sub-activity A11. A41 is controlled by the internal constraints such as decided scope, technologies obtained from A12, A13 and A14, and the output of A41 is converted to the constraints to A4-level activities (i.e. A42, A43, and A44). The tools and mechanisms provided to all A4-level activities (e.g. simulation models, databases, knowledge and know-how) should be provided from A7 which is managed by the administrator of A1. This activity is demonstrated by the case studies Chapter 4. For example, **Tables 4-2** and **4-3** are the data obtained from databases or generated by the simulation models (e.g. simulation of renewable energy-based hydrogen generation potential described by **Eq. 4-1** to **4-4**). The outputs from A4 activities will be fed back to A1 and scenarios are also transferring to the A5 sub-activities.

Figure 5-9 shows sub-activities of the scenario evaluation that are decomposed to A51 to A57: manage S1-A5-level activities, decide objective for evaluations, evaluate environmental aspects, evaluate economic aspects, generate graphical representation, evaluate other indicators, and analyze overall results of the evaluations. First, A51 receives an order from A11 to execute this sub-activity. It is supported by management skills/ facilities provided and controlled by internal constraints generated from other sub-activities. In the same way, all inputs of A51 are converted into the internal constraints to A5-level activities. A52 is the activity to decide objectives for evaluations. The input of A52, which is generated by A4 activity, is converted to evaluating aspects in other A5-level activities. For example, the evaluation of the environmental aspects (i.e. A53) is based on the input data generated from A52. To execute the evaluations of A53 and A54, evaluation method (e.g. LCA guidelines) and simulation models (e.g. **Eq.4-5** to **4-12** for cost optimization) are provided. Then the results from A53 and A54 become the input to generate graphical representation (A55) via the provided visualization tool proposed in this thesis (**Eq. 3-1** to **3-9**, i.e. **P**,**U**, **I** curves). The graphical results which are the outputs from A55 then become mechanism of A57 activity. The evaluated results are either transferring to A6 activity or become feedback information to the A52 activity to re-decide the objective.

The graphical representation proposed in this study is included in this activity, which should combine other environmental, economic and social aspects to analyze overall results of the evaluations and to decide technology introduction strategy A6.

Furthermore, activity A7: provide resource is as an important activity for the administrators. All the resources (i.e. knowledge and know-how, simulation model, existing databases, evaluation method, human resources) needed within this model are managed by the administrators of A1 and will be allocated to the appropriate activities.

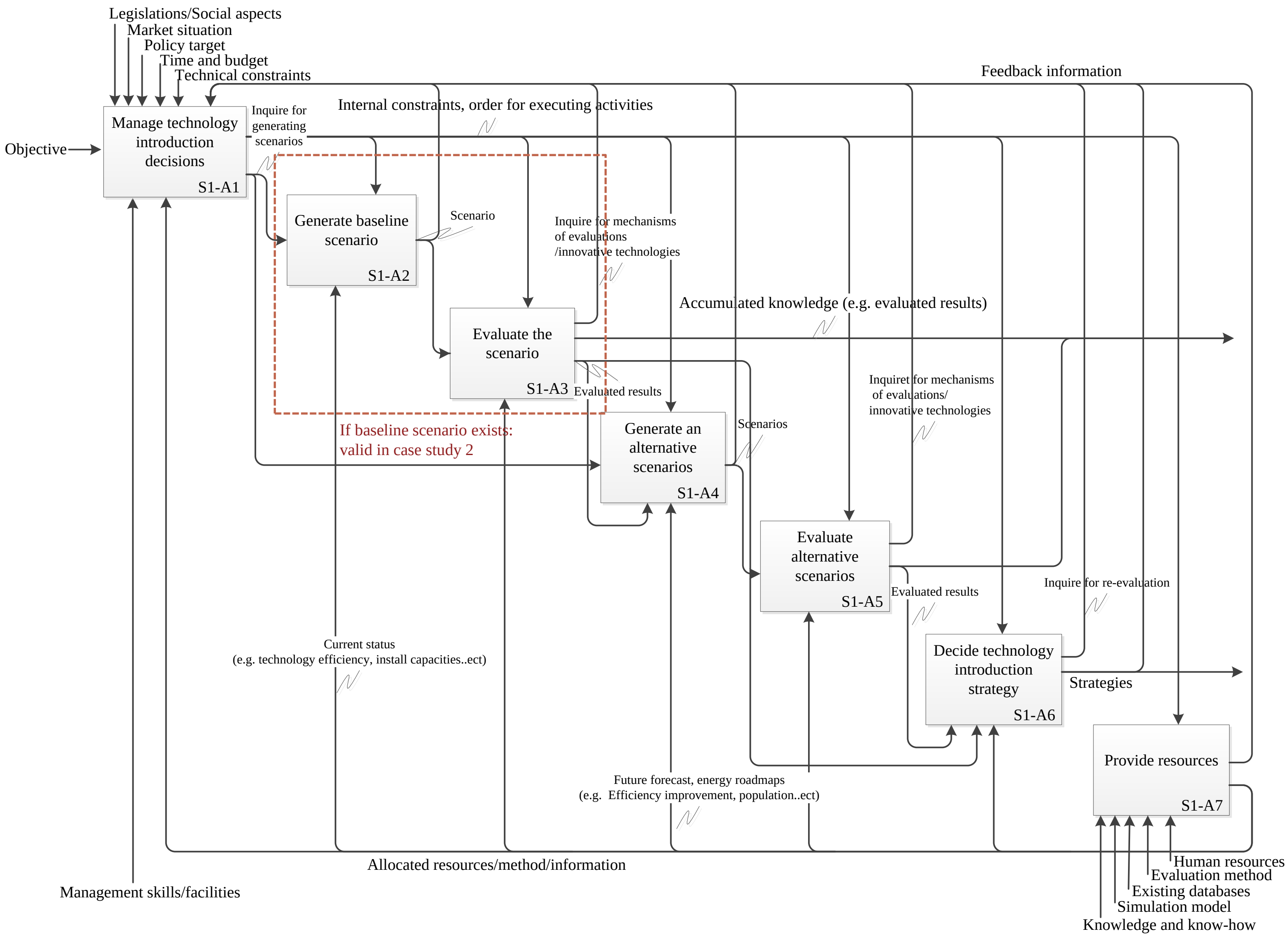


Figure 5-6 Main-level of activity of S1-A0 (overview of the proposed framework)

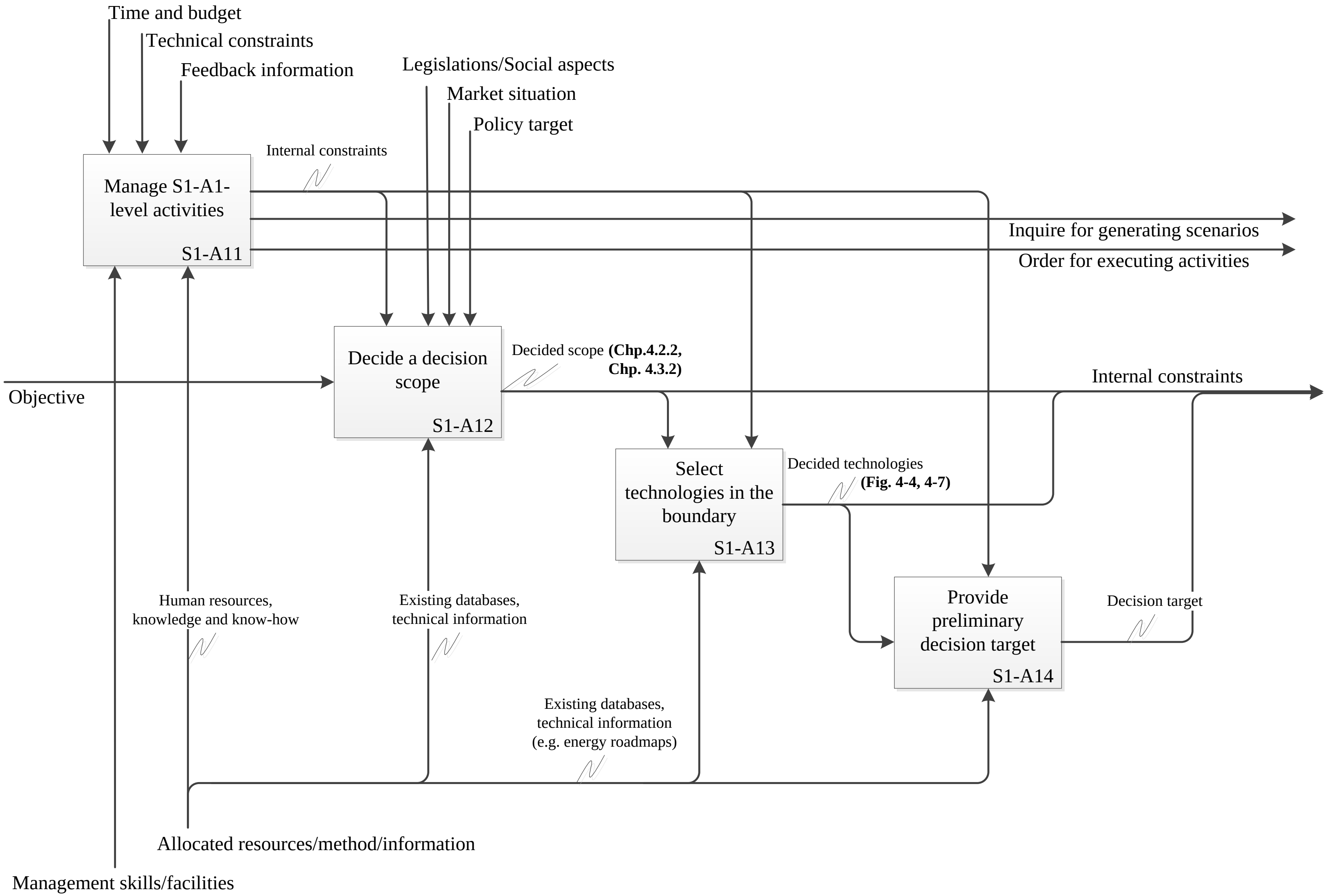


Figure 5-7 Activities A11-A14 of the model S1: sub-activities of the activity A1

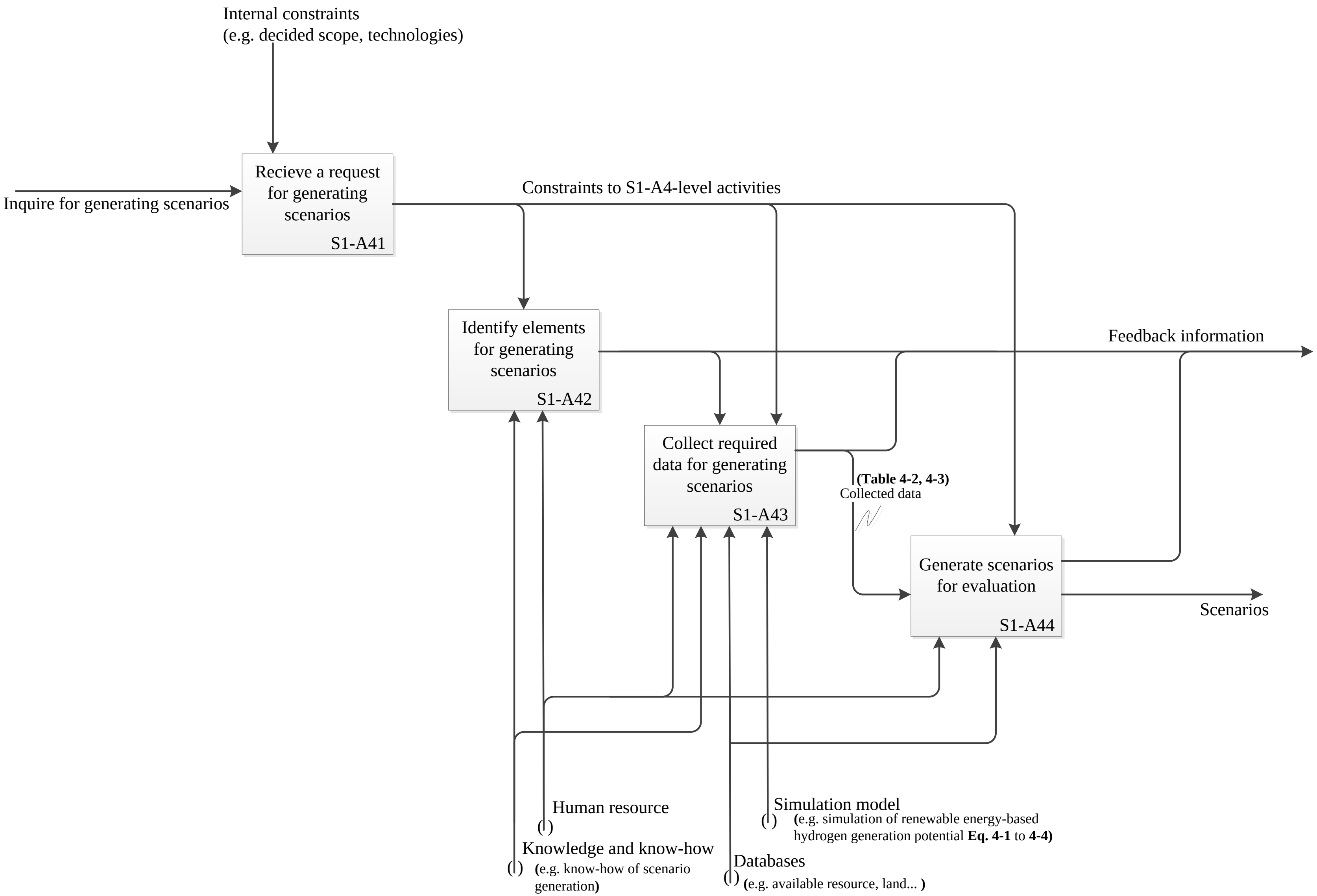


Figure 5-8 Activities A41-A44 of the model S1: sub-activities of the activity A4

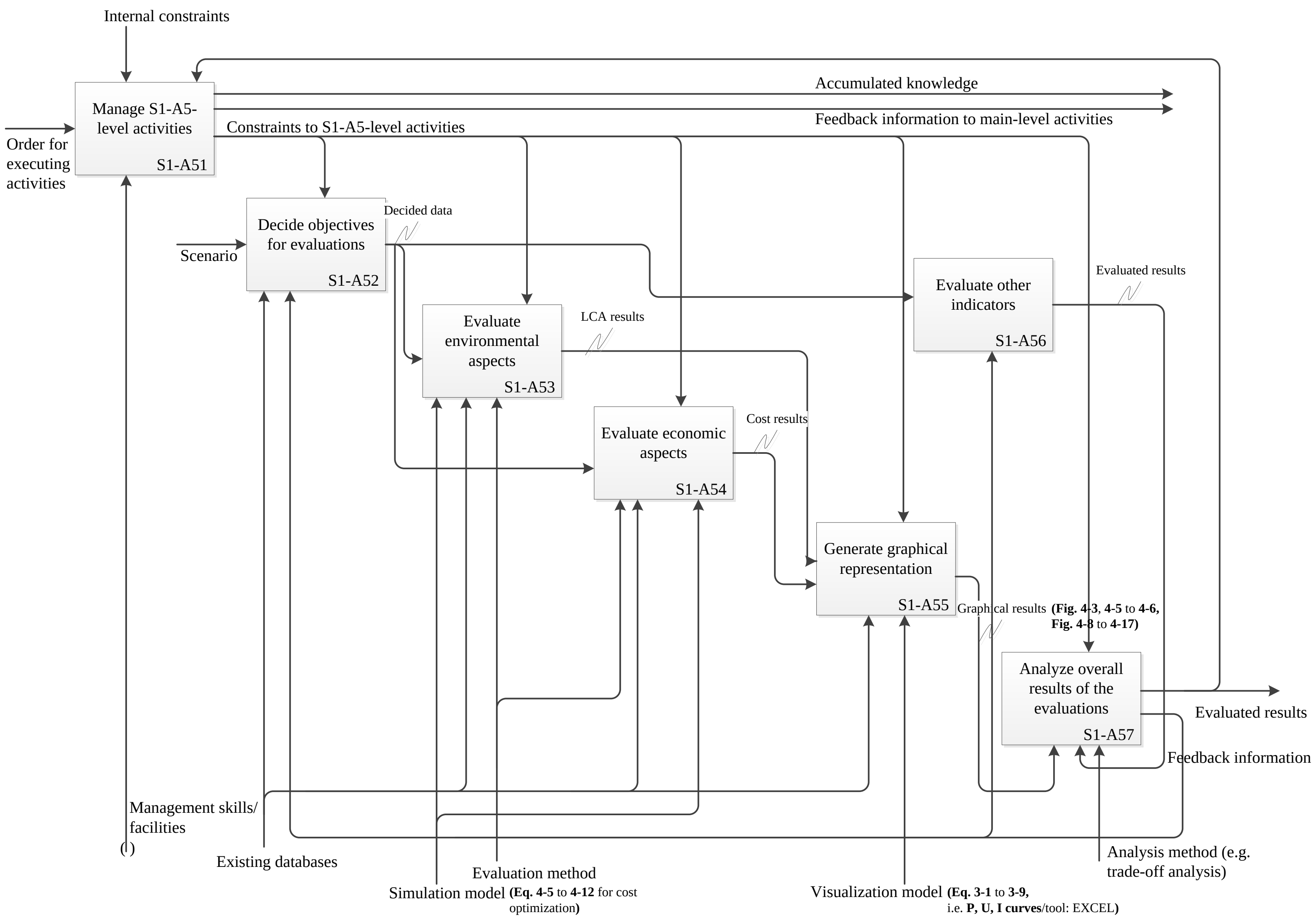


Figure 5-9 Activities A51-A57 of the model S1: sub-activities of the activity A5

5.4 Summary

In this chapter, the framework of developing technology introduction strategies was described by applying a standardized activity model, IDEF0. By using IDEF0, the procedures in the activities are performed step-by-step, which is particularly helpful for stakeholders in the system. Researchers and policy-makers in governmental agency can realize the role of certain technology in whole system domain. Therefore, they can concentrate on either research and development or making resource and cost-effective policies. At the same time, information reveals the trade-offs between different interests, showing the possibility for decision makers for designing a preferable technology combination.

CHAPTER 6 CONCLUSIONS AND DISCUSSIONS

A framework for developing technology introduction strategies was proposed in this study, using a visualized analysis approach that comprehensively assesses combinations of multiple technologies. The achievements are summarized as follows: the framework (1) helps our understanding of scenario performance and behaviors for implementing multiple technologies, (2) identifies the relationships among different evaluation indices and trade-offs in between, and (3) visualizes various scenarios of technology introduction while also considering time as a factor. The method allows to link possible future technology options within multiple-index contexts in a time frame, which is seen as an essential factor in the development of technology introduction strategies.

Case studies on hydrogen-related technology in Taiwan and electricity-based system in Japan were performed to demonstrate the applicability of the proposed methodology. The two case studies were represented two types of systems design: grassroots and retrofit designs that require different tasks in the development processes.

Finally, the developed framework was represented by using a standardized activity modeling method, IDEF0, to hierarchically clarify exact activities with information flows in executing the process of strategic decision making. The collaboration and relationship among three types of stakeholders in generating new technology strategies are described by the flows of information among the three IDEF0 models, which incorporate management, assessment, and development on the hierarchical basis.

Furthermore, the proposed method has a potential to be applied in other systems if technologies in that system provide/share similar function or resource. For example, analyses for an integrated energy system including electricity, heat, fuel and chemicals (e.g. petroleum products) will help generate global, not just local, optimum solutions. Because these sorts of systems can be very complicated, visualized analyses are helpful in organizing information from different aspects. As future competitiveness for resources is likely to become more severe, a strategic manner of resource allocation should play an important role in developing our vision of the future society. This method provides an approach for designing a future society, and can be generalized for each region by defining local constraints.

In summary, this dissertation presents a framework for developing technology introduction strategies by visualizing different scenario performance and behaviors.

CHAPTER 7 RECOMMENDATIONS FOR FUTURE WORK

The graphical representation methodology provides a framework for database that is needed for evaluation of multiple emerging technologies. Establishment of such database shall facilitate and catalyze development of technologies that could most efficiently reduce environmental impacts. There are several expected directions shown as follows:

- The proposed method can be extended and applied in more fields. For example, **Figure 7-1** shows the possibility to assess different purposes of biomass utilization (e.g. to design a sustainable biomass-derived energy and material system). The two green axes represent the different purposes of biomass utilization, and orange axis is environmental impact associated with technologies application. If a% of material and b% of energy in the society are provided by biomass, all possible environmental impacts can be calculated. The blue surface indicates the maximum environmental impact, and red surface indicates the minimum environmental impact, and the impact within all collections of technologies chosen will lie on the space somewhere between blue and red surfaces. It is expected to help understand the trade-offs between different interests, and further achieve the systems effectiveness of resource utilization.

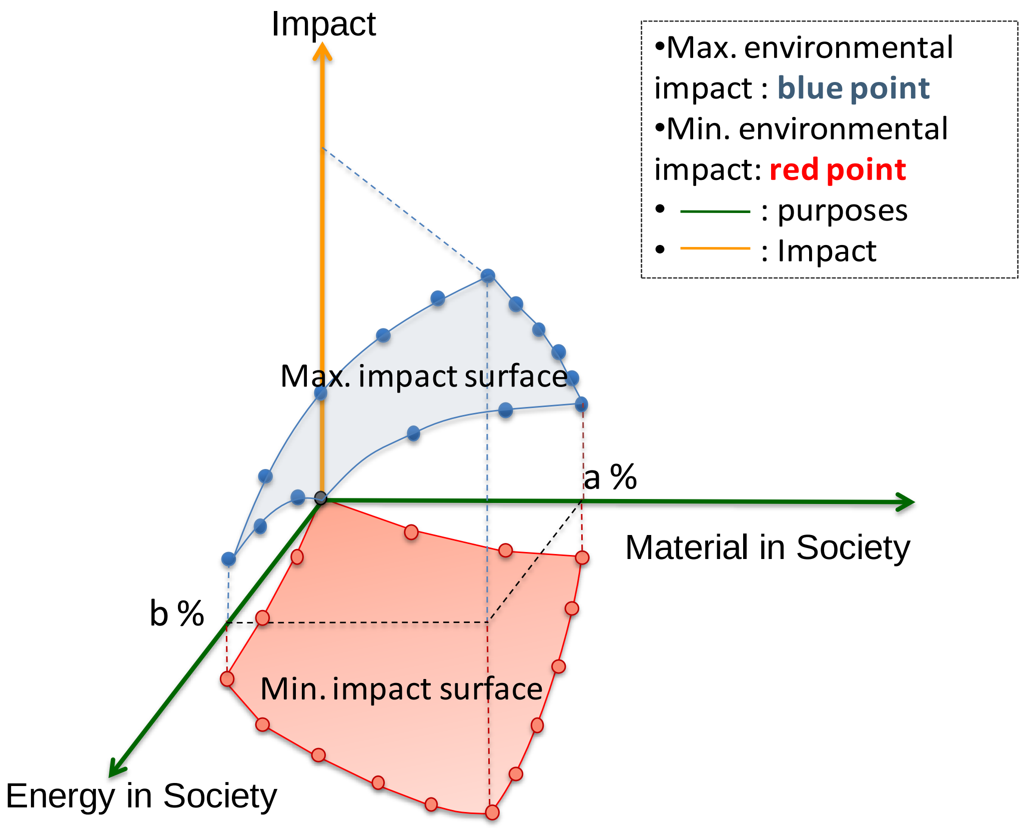


Figure 7-1 The scheme of graphical representation with multi-purpose

- Extension of the covered aspects increases the comprehensiveness of the framework. Currently, the visualization method covers environmental impact and economic aspect (i.e. GHG emission and power generation cost). Integrations of other aspects such as risk assessment, social acceptance show a great importance to achieve a more comprehensive decision-making framework.

Nomenclature

A_i	Residential building roof area in city or county i
D_j	Average travel distance of vehicle j
E_{CO_2}	Total CO_2 emission
E_{PV}	PV power generation
$EF_{CO_2,j}$	CO_2 emission factor for fuel used in vehicle j
i	cities, counties
I_{max}	Maximum environmental impact of applying composite technology
I_{min}	Minimum environmental impact of applying composite technology
I curve	Impact curve
j	Passenger car, motorcycle, trucks
M_j	Average fuel consumption rate of vehicle j
P_i	Power production per m^2 in a year in city or county i, Pi is related to solar irradiation at each location
P_{max}	Maximum environmental impact induced by the production process
P_{min}	Minimum environmental impact induced by the production process
P curve	Production curve
U_{max}	Maximum emission reduction from the utilization process
U_{min}	Minimum emission reduction from the utilization process
U curve	Utilization curve

Abbreviations

BAU	Business-as-usual
EV	Electric vehicles
GCC	Gas combine cycle
GHG	Greenhouse gas
IDEF0	Type-zero method of Integrated Definition Language
LCA	Life cycle assessment
LNG	Liquid natural gas
PHV	Plug-in hybrid vehicles
PV	Photovoltaic
UNFCCC	United Nations Framework Convention on Climate Change
WTs	Wind turbines

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APPENDIX

Source code of the graphical representation tool

The graphical representation is used for analyzing the consequences of technology introduction, along with arbitrary number of relevant scenarios. For providing an easy way to communicate, the representation method is implemented on Microsoft® Office Excel described in VBA (Visual Basic for Application) code shown in this appendix.

- **Code for accumulating inventory data of production curves**

```
Sub makedataP()

    Dim lRowP As Integer
    Dim myRngP As Range
    lRowP = Worksheets("Production").Range("B2").End(xlDown).Row
    used = Worksheets("Production").UsedRange.Rows.Count

    For a = 1 To lRowP - 2
        Range("A" & a + 2) = a
    Next a

'--------------------------
'Clear data
'--------------------------

    Sheets("Production").Range("G3", "V" & used).ClearContents
'------------------------------
'Copy production data to Pmin
```

```
'------------------------------
    With Worksheets("Production")

        '2010
          Range(Cells(3, 1), Cells(lRowP, 4)).Select
          Selection.Copy

          Range("G3").PasteSpecial Paste:=xlPasteValues

          Set myRngP = Range("G3", "J" & lRowP)
          myRngP.Sort _
              Key1:=Range("J2"), _
              Order1:=xlAscending, _
              Orientation:=xlTopToBottom
    End With

        For b = 1 To lRowP - 2
          Range("K" & b + 2) = _
          Range("I" & b + 2) * Range("J" & b + 2)

        Next b
  '-------------------------------
  'Pmin Accumulation
  '-------------------------------

'2010
    For i = 3 To lRowP

        Range("L" & i).Select
        ActiveCell.FormulaR1C1 = "=R[-1]C+RC[-3]"

        Range("M" & i).Select
        ActiveCell.FormulaR1C1 = "=R[-1]C+RC[-2]"


    Next i
```

```
'------------------------------
'Copy production data to Pmax
'------------------------------
    '2010
     With Worksheets("Production")

            Range(Cells(3, 1), Cells(lRowP, 4)).Select
            Selection.Copy

            Range("P3").PasteSpecial Paste:=xlPasteValues

            Set myRngP = Range("P3", "S" & lRowP)
            myRngP.Sort _
                Key1:=Range("S3"), _
                Order1:=xlDescending, _
                Orientation:=xlTopToBottom
    End With

        For c = 1 To lRowP - 2
            Range("T" & c + 2) = _
            Range("R" & c + 2) * Range("S" & c + 2)

        Next c

    For i = 3 To lRowP

        Range("U" & i).Select
        ActiveCell.FormulaR1C1 = "=R[-1]C+RC[-3]"

        Range("V" & i).Select
        ActiveCell.FormulaR1C1 = "=R[-1]C+RC[-2]"


    Next i
```

- **Code for generating production curves**

```
Sub makefigure()
Dim d As Integer
Dim e As Integer

    '------------------------------
    'clear the content of the charts
    '------------------------------
    For d = 1 To ActiveSheet.ChartObjects.Count
        ActiveSheet.ChartObjects(d).Activate
        ActiveChart.ChartArea.ClearContents
    Next d



    '------------------------------
    'plot chart Pmin 2010
    '------------------------------
    maxrow = Range("L2").End(xlDown).Row
    ActiveSheet.ChartObjects("2010Pmin").Activate
       With ActiveChart

        With .Axes(xlCategory)
            .HasTitle = True
             .HasMajorGridlines = True
             .AxisTitle.Text = Worksheets("Production").Range("C1")
        End With



         With .Axes(xlValue)
             .HasTitle = True
             .AxisTitle.Text = Worksheets("Production").Range("D1")
        End With

      End With
```

```
ActiveChart.ChartTitle.Text = "2010Pmin"
ActiveChart.ChartType = xlXYScatterSmoothNoMarkers

For d = 1 To maxrow - 2

    ActiveChart.SeriesCollection.NewSeries
    ActiveChart.SeriesCollection(d).XValues = Range("L" & d + 1, "L" & d + 2)
    ActiveChart.SeriesCollection(d).Values = Range("M" & d + 1, "M" & d + 2)
    ActiveChart.SeriesCollection(d).Name = Range("H" & d + 2)
    ActiveChart.SeriesCollection(d).Border.ColorIndex = Range("G" & d + 2).Value +
2

    Next d

'------------------------------
'plot chart 2010Pmax
'------------------------------

maxrowp = Range("U2").End(xlDown).Row
ActiveSheet.ChartObjects("2010Pmax").Activate
  With ActiveChart

     With .Axes(xlCategory)
         .HasTitle = True
         .HasMajorGridlines = True
         .AxisTitle.Text = Worksheets("Production").Range("C1")
    End With


     With .Axes(xlValue)
         .HasTitle = True
         .AxisTitle.Text = Worksheets("Production").Range("D1")
    End With

  End With
ActiveChart.ChartTitle.Text = "2010Pmax"
```

```
ActiveChart.ChartType = xlXYScatterSmoothNoMarkers

For e = 1 To maxrowp - 2

    ActiveChart.SeriesCollection.NewSeries
    ActiveChart.SeriesCollection(e).XValues = Range("U" & e + 1, "U" & e + 2)
    ActiveChart.SeriesCollection(e).Values = Range("V" & e + 1, "V" & e + 2)
    ActiveChart.SeriesCollection(e).Name = Range("Q" & e + 2)
    ActiveChart.SeriesCollection(e).Border.ColorIndex = Range("P" & e + 2).Value + 2
Next e

'------------------------------
'plot chart 2010PIntegrated
'------------------------------
maxrowp = Range("U2").End(xlDown).Row
ActiveSheet.ChartObjects("2010PIntegrated").Activate
With ActiveChart

    With .Axes(xlCategory)
        .HasTitle = True
         .HasMajorGridlines = True
         .AxisTitle.Text = Worksheets("Production").Range("C1")
    End With


     With .Axes(xlValue)
         .HasTitle = True
         .AxisTitle.Text = Worksheets("Production").Range("D1")
    End With

  End With

ActiveChart.ChartTitle.Text = "2010PIntegrated"
ActiveChart.ChartType = xlXYScatterSmoothNoMarkers

For d = 1 To maxrowp - 2
```

```
            ActiveChart.SeriesCollection.NewSeries
            ActiveChart.SeriesCollection(d).XValues = Range("L" & d + 1, "L" & d + 2)
            ActiveChart.SeriesCollection(d).Values = Range("M" & d + 1, "M" & d + 2)
            ActiveChart.SeriesCollection(d).Name = Range("H" & d + 2)
            ActiveChart.SeriesCollection(d).Border.ColorIndex = Range("G" & d + 2).Value +
2

        Next d

        For e = 1 To maxrowp - 2

            ActiveChart.SeriesCollection.NewSeries
            ActiveChart.SeriesCollection(e + maxrowp - 2).XValues = Range("U" & e + 1, "U"
& e + 2)
            ActiveChart.SeriesCollection(e + maxrowp - 2).Values = Range("V" & e + 1, "V" &
e + 2)
            ActiveChart.SeriesCollection(e + maxrowp - 2).Border.ColorIndex = Range("P" &
e + 2).Value + 2
            ActiveChart.Legend.LegendEntries(maxrowp - 1).Delete

        Next e

End Sub
```

- **Code for generating Utilization curves**

It is similar to the way of generating Production curve, while worksheet should be changed as “Utilization”.

- **Code for generating impact curves**

```
Sub SortAll()

'----------
' Clear data
'----------
```

```
Dim used As Integer
used = Worksheets("Total").UsedRange.Rows.Count


Worksheets("Total").Range("A2", "Z" & used).Font.ColorIndex = 1
Worksheets("Total").Range("A3", "Z" & used).ClearContents
Worksheets("Total").Range("AD3:AE5").ClearContents

'-----------------------
' Copy data from production
'-----------------------

   '2010

      Worksheets("Production").Activate
      maxrow = Range("L1").End(xlDown).Row


      Worksheets("Production").Range("L2", "L" & maxrow).Copy
      Worksheets("Total").Range("A2").PasteSpecial Paste:=xlPasteValues
      Worksheets("Production").Range("J3", "J" & maxrow).Copy
      Worksheets("Total").Range("B3").PasteSpecial Paste:=xlPasteValues
      Worksheets("Total").Range("A2", "B" & maxrow).Font.ColorIndex = 3
      Worksheets("Production").Range("U2", "U" & maxrow).Copy
      Worksheets("Total").Range("O2").PasteSpecial Paste:=xlPasteValues
      Worksheets("Production").Range("S3", "S" & maxrow).Copy
      Worksheets("Total").Range("P3").PasteSpecial Paste:=xlPasteValues
      Worksheets("Total").Range("O2", "P" & maxrow).Font.ColorIndex = 3


'----------------------------
' Copy data from utilization
'------------------------

  '2010
      Worksheets("Utilization").Activate
```

```
    Maxrowu = Range("L3").End(xlDown).Row
    Worksheets("Utilization").Range("L3", "L" & Maxrowu).Copy
    Worksheets("Total").Range("A" & maxrow + 1).PasteSpecial Paste:=xlPasteValues

    Worksheets("Utilization").Range("J3", "J" & Maxrowu).Copy
    Worksheets("Total").Range("B" & maxrow + 1).PasteSpecial Paste:=xlPasteValues

    Worksheets("Utilization").Range("U3", "U" & Maxrowu).Copy
    Worksheets("Total").Range("O" & maxrow + 1).PasteSpecial Paste:=xlPasteValues

    Worksheets("Utilization").Range("S3", "S" & Maxrowu).Copy
    Worksheets("Total").Range("P" & maxrow + 1).PasteSpecial Paste:=xlPasteValues


'--------------------
'sort data
'---------------------

'2010
Worksheets("Total").Activate

With Worksheets("Total")
    Range("A3", "B" & maxrow - 1 + Maxrowu - 1).Sort _
    Key1:=Range("A2"), _
    Order1:=xlAscending

End With



With Worksheets("Total")
    Range("O3", "P" & maxrow - 1 + Maxrowu - 1).Sort _
    Key1:=Range("O2"), _
    Order1:=xlAscending

End With
```

```
'------
'Data Arrangement
'--------

'2010

    Dim i As Integer
    Dim j As Integer
    Dim l As Integer

    maxrowI = Range("A1").End(xlDown).Row

    For i = 2 To maxrowI - 1
        Range("E" & i + 1) = Range("A" & i + 1) - Range("A" & i)
    Next i

    For i = 2 To maxrowI - 1
        Range("S" & i + 1) = Range("O" & i + 1) - Range("O" & i)
    Next i


      For j = 3 To maxrowI
            If Range("B" & j).Font.ColorIndex = 3 Then
                Range("F" & j) = Range("B" & j)
        End If

      Next j

     For j = 3 To maxrowI
            If Range("P" & j).Font.ColorIndex = 3 Then
                Range("T" & j) = Range("P" & j)
        End If

    Next j

        For l = 3 To maxrowI
```

```
            If Range("B" & l).Font.ColorIndex = 1 Then
                Range("G" & l) = Range("B" & l)
            End If
        Next l

     For l = 3 To maxrowI
            If Range("P" & l).Font.ColorIndex = 1 Then
                Range("U" & l) = Range("P" & l)
            End If
        Next l

'------------
'Data autofill
'-------------
    Dim k As Integer
    Dim m As Integer

'2010
    maxrowp = Cells(Rows.Count, 6).End(xlUp).Row
    Maxrowu = Cells(Rows.Count, 7).End(xlUp).Row
    Maxrowp2 = Cells(Rows.Count, 20).End(xlUp).Row
    Maxrowu2 = Cells(Rows.Count, 21).End(xlUp).Row


        For k = maxrowp To 1 Step -1
            If Range("F" & k) = "" Then
                Range("F" & k, "F" & k + 1).FillUp
            End If
        Next k

        For k = Maxrowp2 To 1 Step -1
            If Range("T" & k) = "" Then
                Range("T" & k, "T" & k + 1).FillUp
            End If
        Next k
```

```
        For m = Maxrowu To 1 Step -1
            If Range("G" & m) = "" Then
                Range("G" & m, "G" & m + 1).FillUp
            End If
        Next m

         For m = Maxrowu2 To 1 Step -1
            If Range("U" & m) = "" Then
                Range("U" & m, "U" & m + 1).FillUp
            End If
        Next m

'-----------------
'Accumulation
'-----------------
 '2010
    For i = 1 To maxrowp - 2
        Range("H" & i + 2) = Range("E" & i + 2) * Range("F" & i + 2)
    Next i

    For j = 1 To Maxrowu - 2
         Range("I" & j + 2) = Range("E" & j + 2) * Range("G" & j + 2)

    Next j



    For i = 3 To maxrowp

        Range("J" & i).Select
        ActiveCell.FormulaR1C1 = "=R[-1]C+RC[-2]"

    Next i

    For j = 3 To Maxrowu
```

```
            Range("K" & j).Select
            ActiveCell.FormulaR1C1 = "=R[-1]C+RC[-2]"

        Next j
         For i = 1 To Maxrowp2 - 2
            Range("V" & i + 2) = Range("S" & i + 2) * Range("T" & i + 2)
        Next i

        For j = 1 To Maxrowu2 - 2
             Range("W" & j + 2) = Range("S" & j + 2) * Range("U" & j + 2)

        Next j

        For i = 3 To Maxrowp2

            Range("X" & i).Select
            ActiveCell.FormulaR1C1 = "=R[-1]C+RC[-2]"

        Next i

        For j = 3 To Maxrowu2

            Range("Y" & j).Select
            ActiveCell.FormulaR1C1 = "=R[-1]C+RC[-2]"

        Next j

'----------
  ' Calculate i
    '---------
'2010
    Dim Imin As Integer
    Dim vData As Variant
    Dim Imin2 As Integer
    Dim vData2 As Variant
```

```
        vData = Array(maxrowp, Maxrowu)
        vData2 = Array(Maxrowp2, Maxrowu2)

        Imin = Application.WorksheetFunction.Min(vData)
        Imin2 = Application.WorksheetFunction.Min(vData2)

        For i = 2 To Imin

        Range("L" & i) = Range("J" & i) + Range("K" & i)

        Next i

        For i = 2 To Imin2

        Range("Z" & i) = Range("X" & i) + Range("Y" & i)

        Next i

Call makeIcurve

End Sub


Sub makeIcurve()

        maxrowp = Cells(Rows.Count, 6).End(xlUp).Row
        Maxrowu = Cells(Rows.Count, 7).End(xlUp).Row
        Maxrowp2 = Cells(Rows.Count, 20).End(xlUp).Row
        Maxrowu2 = Cells(Rows.Count, 21).End(xlUp).Row


    Dim Imin As Integer
    Dim vData As Variant
    Dim Imin2 As Integer
    Dim vData2 As Variant
```

```
vData = Array(maxrowp, Maxrowu)
vData2 = Array(Maxrowp2, Maxrowu2)
Imin = Application.WorksheetFunction.Min(vData)
Imin2 = Application.WorksheetFunction.Min(vData2)

'-----------------------------
'clear the content of the charts
'-----------------------------
For d = 1 To ActiveSheet.ChartObjects.Count
    ActiveSheet.ChartObjects(d).Activate
    ActiveChart.ChartArea.ClearContents
Next d

'-----------------------------
'plot chart Imin
'-----------------------------
'2010
 ActiveSheet.ChartObjects("2010Imin").Activate
 With ActiveChart

    With .Axes(xlCategory)
        .HasTitle = True
         .HasMajorGridlines = True
         .AxisTitle.Text = Worksheets("Production").Range("C1")
    End With


     With .Axes(xlValue)
         .HasTitle = True
         .AxisTitle.Text = Worksheets("Production").Range("D1")
    End With

  End With
ActiveChart.ChartTitle.Text = "2010 Imin"
ActiveChart.ChartType = xlXYScatterSmoothNoMarkers
```

```
        ActiveChart.SeriesCollection.NewSeries
        ActiveChart.SeriesCollection(1).XValues = Range("A2", "A" & Imin)
        ActiveChart.SeriesCollection(1).Values = Range("L2", "L" & Imin)
        ActiveChart.SeriesCollection(1).Name = Range("D1")

    '-----------------------------
    'plot chart Imax
    '-----------------------------

'2010

    ActiveSheet.ChartObjects("2010Imax").Activate
    With ActiveChart

        With .Axes(xlCategory)
            .HasTitle = True
             .HasMajorGridlines = True
             .AxisTitle.Text = Worksheets("Production").Range("C1")
        End With



         With .Axes(xlValue)
             .HasTitle = True
             .AxisTitle.Text = Worksheets("Production").Range("D1")
        End With

      End With
    ActiveChart.ChartTitle.Text = "2010 Imax"
    ActiveChart.ChartType = xlXYScatterSmoothNoMarkers

        ActiveChart.SeriesCollection.NewSeries
        ActiveChart.SeriesCollection(1).XValues = Range("O2", "O" & Imin2)
        ActiveChart.SeriesCollection(1).Values = Range("Z2", "Z" & Imin2)
        ActiveChart.SeriesCollection(1).Name = Range("R1")
```

```
'------------------------------
'plot chart IIntegrated
'------------------------------

'2010

ActiveSheet.ChartObjects("2010IIntegrated").Activate
With ActiveChart

        With .Axes(xlCategory)
                .HasTitle = True
                  .HasMajorGridlines = True
                  .AxisTitle.Text = Worksheets("Production").Range("C1")
        End With



          With .Axes(xlValue)
                  .HasTitle = True
                  .AxisTitle.Text = Worksheets("Production").Range("D1")
        End With

    End With
ActiveChart.ChartTitle.Text = "2010 IIntegrated"
ActiveChart.ChartType = xlXYScatterSmoothNoMarkers



        ActiveChart.SeriesCollection.NewSeries
        ActiveChart.SeriesCollection(1).XValues = Range("A2", "A" & Imin)
        ActiveChart.SeriesCollection(1).Values = Range("L2", "L" & Imin)
        ActiveChart.SeriesCollection(1).Name = Range("D1")

        ActiveChart.SeriesCollection.NewSeries
        ActiveChart.SeriesCollection(2).XValues = Range("O2", "O" & Imin2)
        ActiveChart.SeriesCollection(2).Values = Range("Z2", "Z" & Imin2)
        ActiveChart.SeriesCollection(2).Name = Range("R1")
```

- **Code for calculating three indicators**

```
'----------------------------------------
'Find minimum and maximum data
'----------------------------------------

    '2010

    Dim max As Double
    Dim Min As Double
    Dim lngYmax As Integer
    Dim lngYMin As Integer

        max = Application.WorksheetFunction.max(Range("Z2", "Z" & Imin2))
        lngYmax = Worksheets("Total").Cells.Find(max).Row
           Range("AD4") = Range("O" & lngYmax)
            Range("AE4") = max

         Min = Application.WorksheetFunction.Min(Range("L2", "L" & Imin))
         lngYMin = Worksheets("Total").Cells.Find(Min).Row
            Range("AD3") = Range("A" & lngYMin)
            Range("AE3") = Min

   For i = 2 To Imin - 1
           If Range("L" & i).Value < 0 And Range("L" & i + 1).Value > 0 Then
            Range("AD5") = -Range("L" & i) / (Range("L" & i + 1) - Range("L" & i)) *
Range("E" & i + 1) + Range("A" & i)
        ElseIf Range("Z" & i).Value > 0 And Range("Z" & i + 1).Value < 0 Then
            Range("AD5") = -Range("Z" & i) / (Range("Z" & i + 1) - Range("Z" & i)) *
Range("S" & i + 1) + Range("O" & i)

   End If

Next i

 End Sub
```