Framework and Evaluation of the Conditions for Companies to Engage in Renewable Energy Transitions under Constraints of Existing Infrastructure

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A thesis submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy

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Kyoto University

September 2021

Abstract

In this period of potential energy transition from fossil fuel to renewable energy (RE), it has been said that the transition will not come about easily, since a large amount of labor, capital, and effort has been put into the existing social systems, which creates inertia or lock-in of the existing system. That is, the inertia against changes in energy infrastructures or production plants is tremendous due to the long investment cycles. Therefore, it becomes a critical issue for society to clarify how to shift to RE under the constraints of the existing system considering the society's inertia, which depends on existing infrastructure. In particular, under the existing system, since companies are one of the major members of the society, and they account for a large amount of CO_2 emissions, the decision-making for the future energy transition of companies plays an important role in the transition from fossil fuel to RE.

In discussions on energy transitions, both macroscopic and microscopic perspectives are essential since it is said that big transitions are the sum of many small ones. Besides, thinking about the microscopic perspective such as decision-making of companies for the energy transition, it is known that companies do not always be rational but often subjective; not only technologies and economics but also psychologic perspective (humanity), in other words, normative and non-normative perspectives are also important from a microscopic point of view. Based on these backgrounds, this work aimed to clarify the conditions that move companies forward to the energy transition under restrictions of existing infrastructures with multiple perspectives, given Japan and some parts of Japan as the study area.

Chapter 1 provided a literature survey on "Energy transitions," "Decision making in renewable energy investments," and "Environmental management," which are keywords of this work, was introduced in order to clarify the position of this work. Based on the literature review, the chronological strategies of replacement and abolishment of retiring power plants should be considered in the energy transition period based on quantitative system modeling. Regarding decision-making in RE investments, few studies attempt to quantify not only the normative decisions but also the non-normative decisions of RE investment companies. Besides, to observe the outcomes of the company's efforts on past and ongoing energy transition, it is important to identify the characteristics of proactive companies in de-carbonization and energy transition from financial and managerial analysis perspectives. (Section 1.2.3).

With regard to "Energy transitions," it was pointed out that the capacity of thermal power plants was usually determined endogenously or given in a single scenario even though existing power plants can confine the future electricity supply and demand system in previous studies. That is, the problem of previous studies seems to lie in the fact that restrictions of existing power plants had not fully been considered. Therefore, the chronological strategies of replacement and abolishment of retiring power plants would be a key factor for the optimal energy mix in the future, and it is crucial to clarify how the difference of strategies works.

As for "Decision making in renewable energy investments," the conventional net present value

(NPV) approach is one of the useful methods of evaluating the investments by a company, and the real options approach may compensate for the demerits of the NPV approach on decision making under uncertainty. However, these normative approaches do not express the non-normative perspectives of the decision-makers, such as influence from personal beliefs, co-workers, and competitors, even though their importance has been recognized. On the other hand, although some previous studies focused on the behavioral decisions of RE investments, they were mostly based on questionnaire surveys or qualitative analysis; few studies have attempted to quantify the values of RE investments from both normative and non-normative perspectives, particularly regarding the decision-making process of power generation companies to invest in large-scale RE. Therefore, this work infers that the conventional normative approaches will be insufficient when governments formulate future policies and design mechanisms for the large-scale introduction of RE under uncertainty, and a new approach that quantifies the non-normative decisions of RE companies is necessary.

Regarding "Environmental management," most previous studies have focused on the correlation between corporate environmental management/social responsibility and financial performance. Few studies have attempted to identify the characteristics of companies that are proactive in de-carbonization and energy transition from financial and managerial analysis perspectives.

That is, there is the novelty of this work in the point to propose a new quantitative approach to examine companies' energy transition from multiple perspectives under constraints of existing infrastructures.

In order to lead to conclusions on this work, in Chapter 1, a novel framework was designed, which expresses multiple perspectives for the energy transition of companies with quantitative approaches. Besides, Chapters 2, 3, and 4 of this work were allocated to a part of the framework, considering Japan and some parts of Japan as the study area. The results and conclusions of each chapter are as follows.

Chapter 2 took a role as the macroscopic perspective of the energy transition in a future-oriented approach. This chapter clarified that the large-scale introduction of variable renewable energy (VRE) with the chronological replacement of retiring thermal power plants would contribute to reducing the total cost during the energy transition, as well as the amount of surplus electricity of RE. In other words, it was pointed out that the energy transition to RE that includes replacing retiring thermal power plants and extending nuclear power plants could be a feasible and realistic scenario from a macroeconomic point of view. With regard to technologies, the introduction of VRE during the energy transition had regional characteristics; PV would be introduced more in the region where the capability of power adjustment by gas-fired power generation is large, and wind power would be more in the region where the capability of power adjustment is small. Besides, in the scenario of replacing retiring power plants, hydrogen as energy storage with inter-regional transportation, which means hydrogen produced by the surplus electricity in a region with larger RE introduction and transferred to another region with the greater hydrogen-fired GTCC capacity, can reduce the total cost, bridge the lack of reserve margin, and promote VRE introduction.

Chapter 3 represented the microscopic perspective of the energy transition in a future-oriented approach. This chapter designed the novel framework of the decision-making process by RE companies. It developed the behavioral decision-making model to examine the decisions of the RE companies under uncertainty. As per the simulation results, the scenario with the replacement of retiring thermal power plants and life extension of nuclear power plants was better from the RE company's income and CO_2 emission point of view, which was consistent with the result of Chapter 2. Besides, it became clear that (1) heavy investments in either PV or wind resulted in decreased VRE capacity despite sufficient financial support, (2) balanced investments in both PV and wind yields a larger VRE capacity in cases of sufficient financial support, and (3) co-worker's suggestions that lowered the decision-makers' reference point (RFP) encourages VRE investments despite insufficient financial support.

Chapter 4 attempted to observe the influence of past and ongoing company's energy transition from meso-scale perspectives. From the financial performance point of view, companies proactive in energy transition had normal or slightly below financial performance. Besides, companies with high financial performance and energy-intensive companies could be relatively less proactive in the energy transition. As per the analysis of CO_2 emissions, companies proactive in energy transition had larger indirect CO_2 emission than direct ones and less CO_2 emission for the company scale. Besides, from the company's management perspective, companies proactive in energy transition are more aware of their "own brand" and "business strategy" than the other companies.

Finally, Chapter 5 applied the results and conclusions of Chapters 2, 3, and 4 to the novel framework in this work and discussed how to encourage the company's energy transition. The effective use of existing infrastructures will be a realistic approach to the large-scale RE introduction from a society point of view. Besides, inter-regional cooperation of RE companies in different regions and negative framing of RE investments from the society will encourage the companies' energy transition. It is also important to overview the outcomes of companies' energy transition from financial performance, CO_2 emissions, and management policy aspects in order to observe the influence of past and ongoing companies' efforts. These processes could make a positive cycle of RE introduction, and this work concluded that inter-regional energy production and cooperation for inter-regional consumption based on the effective replacement of retiring power generation facilities would move companies forward to the energy transition.

Since little previous literature attempted to provide quantitative outcomes of the company's energy transition from both normative and non-normative aspects considering the constraints of existing infrastructures, this work will contribute to provide new knowledge on the company's energy transition based on quantitative analysis and bring suggestive conclusions to future policy-making on the energy transition. Besides, this work proposed several novel frameworks and quantitative models to discuss the work's aim. Although this work applied the frameworks and models to Japan and some parts of Japan are given as the study area, these frameworks and models can be expanded to other regions and countries and be practically expected to contribute a further analysis of the company's energy transition.

Acknowledgments

Firstly, I am grateful to my supervisor Professor Benjamin C. McLellan. He always willingly guided and supported me even though he was very busy, and he gave excellent instructions to me in order to complete my papers and thesis. I truly appreciate his supervision to me.

I would also like to extend my gratitude to my thesis reviewers, Professor Keiichi Ishihara, and Professor Hiroshi Shimoda. Their comments, guidance, and suggestions were very insightful and constructive. Their supervision helped me to improve and complete the work.

I express my sincere appreciation to Dr. Tetsuo Tezuka, Professor Emeritus Kyoto University, President of Japan Society of Energy and Resources. When I visited his laboratory in the Summer of 2018, he welcomed me to join his laboratory and gave me a chance to be a researcher. I learned a lot from him including the impressive philosophy of academic research. I would also like appreciate Professor Seiichi Ogata for his insightful advice in laboratory seminars. Discussion with him greatly helped me to improve my research. I would like to thank Ms. Tomoko Tomomatsu and Ms. Hung Mayumi, the laboratory secretaries. Their continuous kind supports were essential for my research activity. I also appreciate my laboratory members. They have various backgrounds and the discussions with them were very exciting to me.

I am grateful for the cooperation of Mr. Hiromi Ishii and Mr. Takashi Kishine, who were my supervisors in Mitsubishi Power, Ltd. They accepted me to apply to the graduate school, and they sometimes gave me valuable advice on my research.

I also would like to show my appreciation to my father in heaven and my mother in my hometown. They always had encouraged me to learn what I was interested in since I was a little child. I could keep learning thanks to their education and words. I believe that they must be the ones who are most proud of my Ph.D. Thank you.

Finally, I would like to thank my dearest wife and son. When I told her I wanted to learn energy economics in graduate school three years ago, she encouraged me to be a working Ph. D. student even though she was tied up with taking care of the little baby. Without her understanding, support and patience, I could not get here. Also, since I was busy with both my job and research every day, I sometimes could not fully play with my son. However, he always gave me cute smiles and cheered me up the most. Although my challenge to the Ph. D. was tough, I hope one day it will guide his future challenges. Now, as discussed in this thesis, we are facing a transition period. May a good wind always blow in your life, with my sincere appreciation.

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Abbreviations

BFG	Blast Furnace Gas
CAPEX	Capital Expenditure
CVaR	Conditional Value at Risk
FIP	Feed-in Premium
FY	Fiscal Year
GTCC	Gas Turbine Combined Cycle
IPP	Independent Power Producers
KEPCO	Kansai Electric Power Company
LFC	Load-Frequency Control
LNG	Liquified Natural Gas
NDC	Nationally Determined Contribution
NPV	Net Present Value
O&M	Operation & Maintenance
PCA	Principle Component Analysis
PHS	Pumped-storage Hydroelectricity
PV	Photovoltaics
RE	Renewable Energy
RFP	Reference Point
SBT	Science Based Target
SD	Standard Deviation
TSE	Tokyo Stock Exchange
VRE	Variable Renewable Energy

CHAPTER 1. Introduction

1.1 Background

Set sail and catch the wind against the waves. The use of energy was constrained by nature prior to the industrial revolution for a very long time, just as the capabilities of sailing ships were restricted by prevailing winds and persistent ocean currents [1]. In this era, people's lives and also wider economic activities, were carried out under the constraints and risks produced by the natural environment. For example, the Dutch East India Company, founded in 1602 and known as the world's first public company, faced not only economic risks such as price fluctuations of commodities, but also natural risks such as shipwrecks [2]. The company was a union composed of six chambers, and the six chambers and stockholders cooperated and shared the risks of the company's business [2], including the risk caused by nature.

Then, in the mid-18th century, the industrial revolution began in Great Britain. Industries that had been restricted by energy sources from nature such as wind, water, and solar heat were gradually shifted to those that relied on steam power generated from coal [3]. This transition was relatively slow, and it took approximately 100 years from the start of the industrial revolution for coal to reach 25% of the total global energy supply [3]. In Japan, the energy transition followed a similar pathway to western countries after the Meiji restoration in the latter 19th century, but the change in energy sources was more rapid due to the delay in modernization compared to the western countries; The percentage of coal in total primary energy supply increased from 27% in 1890 to 78% in 1930 [4].

As shown in **Figure 1.1**, Japan's energy use dramatically declined in 1945 due to defeat in World War II. After World War II, Japan swiftly increased oil consumption, with oil use equaling coal in 1960. In 1962, oil imports were liberalized, and oil use in primary energy supply exploded toward the 1970s. From the perspective of electricity, in 1951, Japan established the nine regional General Electricity Utilities: Hokkaido, Tohoku, Tokyo, Chubu, Hokuriku, Kansai, Chugoku, Shikoku, and Kyushu Electric Power Companies as a result of the discussion on measures for democratizing the economy, and these regulated companies were to fulfil the responsibility of supplying electricity to each region; Okinawa Electric Power Company joined in 1972 after the reversion of Okinawa to Japan [5]. The ten regulated power utility companies built a stable and robust power transmission system. They developed a centralized power supply system with large-scale power generation facilities in each region to ensure a high-quality power supply.

In 1973 and 1979, Japan experienced the oil crisis, and this led to a deliberate policy and sectoral expansion of diversity in primary energy sources from the 1970s to the 2000s. Japan also pioneered, and then dramatically increased, the import of liquefied natural gas (LNG), with LNG trade contributing to diversify Japan`s source countries for energy imports. In this period, nuclear power generation was also pushed forward in order to reduce the high dependence on imported fossil fuels. On March 11th in 2011, the Tohoku earthquake hit eastern Japan, and the subsequent Fukushima Daiichi nuclear disaster caused by the earthquake and tsunami brought further challenges to the energy system, with immediate temporary shut-downs of nuclear plants. In the following months and years, popular opposition to nuclear power and much stricter safety legislation led to the permanent closure of many plants. As of 2016, the percentage of fossil fuels increased significantly, since most nuclear power plants were not available after the disaster, either due to safety renovation requirements or closure. Japan's energy system has long been characterized by a meager ratio of energy self-sufficiency, but this has been exacerbated, with a ratio of only 12.1% in 2019 [4]. Now, in the 21st century, climate change continues to be one of the most critical issues globally. The transition from the use of fossil fuel as a source of energy to non-carbon energy - especially renewable energy (RE) - is expected to continue to progress. In other words, we need to face the uncertainty and restrictions of nature again, as was the case more than 200 years ago in pre-industrial times, in order to address climate change.

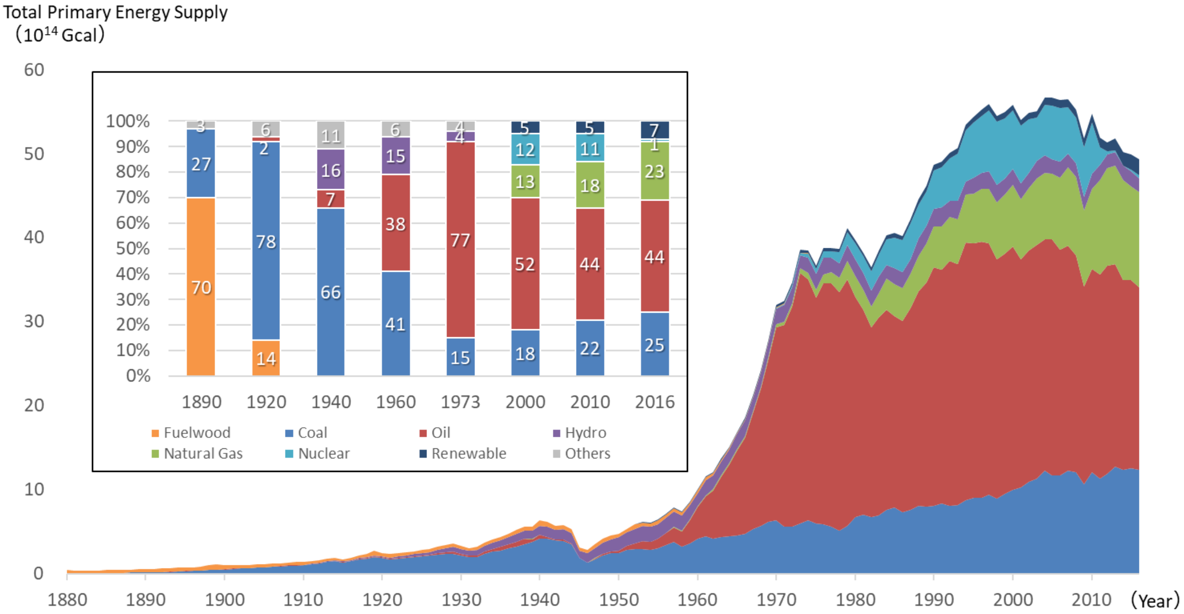


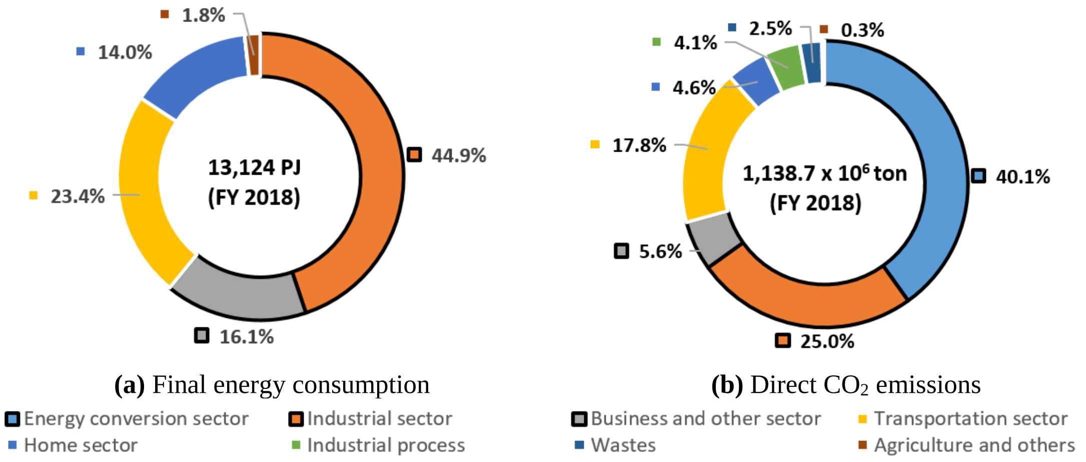
Figure 1.1. Total primary energy supply from the 1880s through the 2010s in Japan, the bar chart shows the percentage of energy sources. (Modified from Ref. [4])

Under these circumstances, the Paris Agreement, adopted in 2015 and signed in 2016, has brought more serious efforts to deal with climate change within the United Nations Framework Convention on Climate Change (UNFCCC). The Paris Agreement aims to hold “the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels” [6]. Each party shall be obliged to set a target of greenhouse gas reduction called a nationally determined contribution (NDC) and pursue domestic mitigation measures [6]. Each country needs to make efforts for the energy transition in line with the NDC, and the Japanese government a set target of 80% CO_2 reduction by 2050 in the action plan for global warming published in 2016 [7].

With regards to the future energy system, distributed energy systems based on RE may be one of the preferable options instead of the existing vertically integrated and centralized energy systems, if we consider aspects such as resilience against natural disasters [8] and employment creation [9]. However, considering the energy transition phase from the current centralized system, it has been highlighted that the transition will not come about easily, since a large amount of labor, capital, and effort has been spent in the evolution of the existing socio-technical systems, and this creates inertia or lock-in of the existing system [10–12]. As Lund mentions, the inertia against changes in energy infrastructure or production plants is tremendous, due to the long investment cycles [13].

According to the theoretical transition framework - the multi-level perspective (MLP) - designed by Geels [14], which is one of the well-used approaches in socio-technical transition analysis, an existing socio-technical regime can be changed to a new regime when a landscape pressurizes the existing regime. A socio-technical regime means a complex of engineering practices, industrial structure, knowledge, culture, etc. that maintains a certain technology, and a landscape is an exogenous environment such as climate, macroeconomics, and demographics. Taking the example of Japan, the Tohoku earthquake and the Fukushima Daiichi nuclear disaster could be considered to be strong pressures from the landscape to the existing regime. After the disaster, deregulation of electric and city gas utilities proceeded, and energy consumption was reduced by approximately 15% in 2016 compared to 2010. However, the energy system remains in the pre-existing regime despite the extreme pressure of the disaster, since the Japanese society is highly dependent on the existing infrastructure, and the existing regime shows high inertia [15,16].

The mainstream literature mentions that energy transitions take many decades [17,18] even though some studies say that future energy transitions may take only a few years or decades [19]. However, there are only 30 years remaining toward 2050, which is the target year for many of the climate policies. If we consider 2050 as a hard deadline for changing towards low carbon energy, it becomes a critical issue for society to clarify how to shift to RE under the constraints of the existing regime considering society's inertia, which is bound into existing infrastructure. In particular, under the existing regime, since companies are one of the major stakeholders in society, and they account for a large amount of CO_2 emissions, decision-making for the future energy transition of companies plays an important role in the transition from fossil fuel to RE. More than 60% of final energy consumption and 70% of the direct CO_2 emissions come from sectors tied to companies in Japan, as shown in **Figure 1.2**. Although approaches to energy transitions should differ depending on the specific sector or business domain, this study focuses on the transition of companies related to electricity and RE investment, since the energy conversion sector accounted for 40% of CO_2 emissions in Japan [4,20] and promotion of electrification is one of the most important factors for the ongoing energy transition. The key question then is, how to encourage companies undertake energy transitions from fossil fuel to RE under restrictions of existing infrastructure? This is interest and motivation of the present work.



(a) Final energy consumption

(b) Direct CO_2 emissions

Figure 1.2. Final energy consumption and direct CO_2 emission by sector in Japan (Visualized from Ref. [4,20])

In discussions on energy transitions, as stated by O'Connor, "Big transitions are the sum of many small ones" [21], both macroscopic and microscopic perspectives are essential. Especially thinking about the microscopic perspective, such as the decision-making of companies with relation to the energy transition, it is known that companies do not always act purely rationally but often make subjectively-influenced decisions. It is not only technologies and economics, but also psychological perspectives - in other words, normative and non-normative perspectives are also important from the microscopic point of view.

Given this background, the present study aims to clarify the conditions that move companies forward in the energy transition under restrictions of existing infrastructures from multiple perspectives: macroscopic and microscopic; techno-economic and psychological; normative and non-normative perspectives, with Japan and regions of Japan as the study areas. When the 'energy transition' is discussed from a company perspective in this thesis, it is focused on the company's contribution to the energy transition at a society level. The following section introduces a literature survey on "Energy transitions," "Decision-making in renewable energy investments," and "Environmental management," which are keywords of this work, in order to clarify the position of this work.

1.2 Literature Review

This section describes the relevant literature, and consists of three sub-sections as follows. The first sub-section (Section 1.2.1) overviews literature regarding energy transitions to clarify the approach of this study from the macroscopic perspective. The second sub-section (Section 1.2.2) introduces previous studies on decision-making, especially focused on RE investments, in order to discuss the microscopic perspective of this work. The third sub-section (Section 1.2.3) provides a literature review of environmental management in order to identify a novel approach for evaluating the performance of companies' efforts on energy transitions.

1.2.1 Energy transitions

When an energy transition is discussed, how the energy transition is defined becomes an essential issue [19]. Though there are no commonly accepted definitions of energy transitions in academic literature, Smil summarizes that "the term energy transition is used most often to describe the changing composition (structure) of primary energy supply" [3]. Sovacool further mentioned that "an energy transition most broadly involves a change in an energy system, usually to a particular fuel source, technology, or prime mover" based on a literature review that defines energy transitions [19]. This study refers to these definitions, and hereafter the "energy transition" means a change in energy sources and technologies from fossil fuels and nuclear power to RE, unless otherwise noted.

With regard to study approaches on energy transitions, the discussion started with exercises in future scenarios, rather than from historical accounts, in the 1950s [21]. These scenario-based approaches mainly focused on changes in energy consumption and the amount of certain energy technologies introduced, from engineering and quantitative perspectives [21]. Since the 1990s, the scope of studies in energy transitions has been expanded from technologies themselves to societies, industries, and economies in which technologies are embedded. Discussions on socio-technical approaches has become active, and are a major part of theoretical and qualitative research streams based on social sciences such as economics and history [22].

Study approaches to energy transitions are summarized in **Table 1.1**, which is generally categorized into quantitative system modeling, socio-technical transition analysis, and initiative-based learning [23–25]. Quantitative system modeling provides a forward-looking perspective of transitions by model-based simulation in line with scenarios tied to technologies, economics, and policies. This approach gives clear suggestions and contributes to creating concrete targets for policy-making. However, the given outcomes tend to overlook the non-rational aspects of transitions due to the abstraction and simplification of real society and technologies.

Socio-technical transition analysis interprets technologies as being embedded in society, and the approach analyzes historical and ongoing transition pathways considering multiple levels of socio-technical system qualitatively and descriptively. The analysis can describe not only technologies and economics but also non-rational aspects of transitions, but has the demerits of less concrete suggestions for the future.

Initiative-based learning engages with concrete projects at the level of individual initiatives such as experiments. This approach aims to foster innovation and upscale innovative sustainability involving various actors such as citizens, businesses, and (local) government. The approach mainly focuses on the local level and the short term, and addresses implementation and learning, which deals with the complexity of actors such as capabilities, positions, and power. However, the methodologies have not been fully standardized, and the applied area of lessons learned is limited. As Geels et al. mention, each approach has unique pros and cons, and full integration of these approaches is not feasible. Still, bridging studies based on different approaches may help address the energy transitions [25].

Table 1.2 shows the key characteristics of energy transition related to this work. Since the current work focuses on future-oriented and long-term aspects of energy transitions with suggestions on the scale of regions, quantitative system modeling will be applied for the macroscopic perspective. However, quantitative system modeling tends to overlook non-rational aspects. Therefore, this work tries to fill this gap by examining the energy transition from both normative and non-normative points of view with the quantitative approach. This work attempts to complement the macroscale approach based on quantitative system modeling from a microscale approach.

With regards to quantitative system modeling, there have been numerous studies on the future energy mix and energy storage in Japan; Shiraki et al. [26] split the whole of Japan into 60 areas and analyzed CO_2 reduction scenarios in 2020 for each area, considering the regional differences in electricity demand and network interconnection. Komiyama et al. [27] showed the outlook for energy supply and demand in 2050 under various scenarios of CO_2 constraints and nuclear power. Nagatomi et al. [28] analyzed the power generation mix in 2040, considering the Load-Frequency Control (LFC) and reserves of each region. They showed that the introduction of RE was limited due to regional differences in the potential of RE, the electricity supply-demand balance. Mitani et al. [29] addressed the economic analysis of hydrogen production by surplus electricity and co-combustion technology. Dohi et al. [30] showed that secondary batteries and hydrogen co-firing were not completely competitive technologies with each other for the large-scale introduction of RE. They also clarified that a mixture of these technologies would lead to a lower total system cost.

In these previous studies, the capacity of thermal power plants was usually determined endogenously with exogenous limits on emissions or given in a single scenario even though existing power plants can constrain the future electricity supply and demand system. That is, the problem of previous studies seems to lie in the fact that restrictions of existing power plants have not fully been considered. Therefore, the chronological strategies of replacement and abolishment of retiring power plants would be a key factor for the optimal energy mix in the future, and it is crucial to clarify how the difference of strategies works.

Table 1.1. Summary of study approaches on energy transition (Modified from Ref. [23–25])

Item	Quantitative system modeling	Socio-technical transition analysis	Initiative-based learning
Conceptions	Provide forward-looking perspective of transitions by model-based simulation in line with scenarios tied to technologies, economics, and policies	Interpret technologies as embedded in society (Socio-technical) Describe and analyze historical and ongoing transition pathways in multiple levels of socio-technical system qualitatively	Engage with concrete projects at the level of individual initiatives such as experiments Aim to foster innovation and upscale innovative sustainability involving various actors such as citizens, businesses, and (local) government
Analytical scale	Global (incl. climate change), national, sector, and regional	Mainly national, sometimes across countries	Mainly local scale
Timeframe	Long-term (decades)	Long-term (decades)	Short-term (5-15 years)
Time orientation	Future projection	Historical and ongoing transition	Transitions in the making
Strengths	- Well established methods - Clear suggestions for high-level policy-making by the observable outcome of variables	- Multi-perspective analysis of transition process of society which includes technological, economic and cultural aspects	- Specific local level implementation and learning, which deals with the complexity of actors such as capabilities, positions, and power
Weaknesses	- Need to abstract and simplify realities in society and technologies for quantified modeling - Tend to overlook non-rational aspects of transitions caused by culture and human behavior	- Less concrete suggestions for policy-making and limited generalization since approaches are descriptive and qualitative - Limited future orientation	- Limited standardized methodologies - Difficult to obtain generalized lessons, especially for entire transitions
Typical Methodologies	Biophysical analysis; climate models, especially focused on human-climate interactions such as GHG emissions. (Ref. on IPCC reports: [31,32]) Techno-economic analysis; focused on technologies and economics to describe future de-carbonized society. (Ref. on the energy mix in Japan:[26–30])	Strategic Niche Management [33,34]; strategically manages new technologies in a protected space (niche), and brings a regime change. Multi-level Perspective [14,35]; analyze transitions of technologies from multi-level perspectives in society. Technological Innovation Systems [36–38]; focuses on the mechanism of technology’s development and growth of technologies.	Transition management [39,40]; focuses on local scales, and organizes concrete frameworks and theories for practicing transitions.

NOTE: In addition to the approaches above, there are some other theories of energy transitions such as Ecological modernization theory, Sociology, and social practice theory, and Political ecology [19].

Table 1.2. Key characteristics of energy transition related to this work

Item		Quantitative system modeling	Socio-technical transition analysis	Initiative-based learning
Concepts		Forward-looking perspective of transitions with mathematical modelling	Interpret technologies as embedded in society (Socio-technical)	Engage with concrete projects such as experiments
Scale	Global	X		
	National, Regional	X	X	
	Local			X
Time orientation	Future	X		
	Historical, Ongoing		X	X
Timeframe	Long-term	X	X	
	Short-term			X
Strengths	Clear suggestions	X		
	Multi-perspective (including non-normative)		X	X

NOTE: "X" in the table means applicable to the characteristics.

1.2.2 Decision making in renewable energy investments

In the field of studies on decision-making, especially under uncertainty, approaches are normally categorized as either normative, descriptive, or prescriptive [41,42]. As summarized in **Table 1.3**, the normative approach focuses on rational decision-making and deductive discussions based on mathematical models, and is typified by expected utility theory. The descriptive approach is a psychological approach that inductively seeks out what human decision-making is, through experimental results, with prospect theory being a common method. The prescriptive approach focuses on supporting the decision-making of individuals who are less rational but aspire to rationality.

In the 16th century, Pascal introduced the idea of "expected value"; when a decision-maker faces a set of choices and the possible outcomes of each choice have different probabilities, the expected value of each choice is given by the sum of the product of each outcome and probability [43] as given by the following equation

$$E(X) = \sum_{i=1}^{N} x_i p_i$$

where, N is a number of choices, X is a random variable ($X = \{x_1, x_2, \dots x_n\}$), $E(X)$ is the expected value of X, p_i is a probability of x_i. The expected value theory assumes that the decision-maker will select the choice with the highest expected value. However, Bernoulli pointed out the insufficiency of expected value theory from the normative decision perspective, referring to the St. Petersburg paradox in the 1730s, which is that a theoretical lottery game leads to a random variable with infinite expected value but the participants feel a very small value of the game in reality [43]. Referring to the paradox, he proposed the expected utility theory instead [43]. John von Neumann and Oskar Morgenstern later addressed the same problem and developed the von Neumann-Morgenstern expected utility theory [44]. In expected utility theory, the idea of "utility" was applied instead of monetary outcomes used in expected value theory, representing a decision-maker's preference based on the satisfaction or pleasure received by a choice, and described by a utility function incorporating personal preference and risk. The theory claims that the decision-maker rationally selects the choice with the highest expected utility from all choices, based on four axioms; axiom of completeness: an individual has well defined preferences, transitivity: the order of preferences is consistent in each option, continuity: the preferences are continuous between each option, and independence: a preference keeps independence irrespective of the another option's probability [44]. The expected utility theory is widely applied in microeconomics and game theory.

On the other hand, Saimon proposed bounded rationality (instead of the perfect rationality of expected utility theory) which claims that a decision-maker seeks a satisfactory choice rather than an optimal one, since the rationality of an individual is limited in reality [45]. Kahneman and Tversky expanded the idea of bounded rationality, and developed prospect theory from a behavioral economics point of view, which is one of the major descriptive approaches. Prospect theory aims to describe the behavior of individuals in reality. The theory proposes that an individual decides based on gains and losses relative to a reference point; where the individual is risk-averse when facing a risky choice leading to gains and risk-seeking in cases leading to losses [46,47]. (See also Appendix B1 for the formulation of prospect theory.) Another behavioral approach, regret theory, takes into account the effect of anticipated regret for decision-making under uncertainty [48–51].

Although the third approach, the prescriptive approach, is sometimes regarded as a part of the normative approach, the prescriptive approach focuses on supporting decision-makers to make rational decisions on a particular issue [41]. Although the prescriptive approach is not mature compared to the normative and descriptive approaches, this approach includes operations research and management science, and has been gaining research interest [42]. Multi-criteria Decision Making (MCDM) is representative of this approach, and some methods of MCDM have been applied to studies of decision-making for RE investment. For example, several studies proposed supporting methods to select options for RE investment with the analytic hierarchy process (AHP) [52–55]. The AHP is one of the well-known MCDM methods to support organizing and analyzing complex decisions by quantifying the weights of decision criteria based on a structured technique [56]. Similarly, Hahn [57] demonstrated guidance of decision-making priorities for private entities in energy sustainability planning based on multi-attribute utility theory (MAUT), in which the total scores for alternatives were determined by the weighted utility scores for individual attributes. Although the prescriptive approach has prompted much research interest [41], this approach has the same issue as the normative approach – it does not sufficiently describe people`s or companies' decisions in reality.

Table 1.3. Summary of study approaches on decision-making

Item	Normative	Descriptive	Prescriptive
Perspective [41]	How "rational" people should make decisions.	How people make decisions.	How less rational people, who aspire to rationality, might do better.
Focused disciplines	Economics (Microeconomics, Game theory)	Psychology, Behavioral economics	Business administration, Engineering
Typical theories / methods	Expected utility theory [43], NPV method, IRR method, Real options [58]	Prospect theory [46,47] Regret theory [48–51] Questionnaire surveys	Operations research (Multi-criteria Decision Making (MCDM), etc.)Management science
Application to decision making for energy investment	Real options [59–62]	Qualitative questionnaire surveys and qualitative analysis [63–66] Quantitative PV investments of households [67] Energy saving investments of individuals [68]	Analytic Hierarchy Process (AHP) [52–55] Multi-attribute Utility Theory (MAUT) [57]

Although decision theories and decision support methods have been developed as stated above, it is known that the approaches of many companies to decision-making are much simpler. The net present value (NPV) method, which is one of the simple methods in the normative approach, is widely applied in decision making for company investments [69,70]. Though the NPV method is regarded as one of the most effective measures for the evaluation of the advantages and disadvantages of investments [59], in reality, companies often do not make investment decisions even if the expected NPV of the investments are positive [71], especially in cases of capital investments under uncertainty, as these decisions are irreversible (once large-scale capital is constructed, it is not readily shut-down without significant loss). The investment behavior of companies, in reality, may differ from their investment criterion given by the conventional NPV approach. To explain this variation, the “value of the option of waiting to invest” has been introduced [58]; if the value of an option to wait is greater than that of the expected NPV of the investment at the current time, then the investment will be postponed. The application of such “real options” approaches became one of the major discussions in decision-making regarding investments under uncertainty including in power generation investment studies [72]. In the real options approach, decision-makers have flexible investment options, and the value of options is evaluated via methods developed for finance such as the binominal model and the Black–Scholes model, in addition to traditional NPV approaches [58,73]. As shown by Kaslow and Pindyck, some electric utility companies are known to have applied real options when they made investment decisions under uncertainty [74]. Several studies have since used real options to evaluate investment in RE [59–62,75], nuclear [76], and thermal power plants [77]. These studies showed the effectiveness of flexibility for decision-makers during decision making on investments under uncertainty. However, as real options still rely on traditional NPV approaches, the problem of previous studies is retained, in the assumption that the decision-makers are supposed to make rational investment decisions. Thus, the question of whether power generation companies actually always make rational decisions persists.

Here, it is important to discuss people`s and companies’ real decisions in society considering the non-normative perspective. As Hodgkinson et al. [78] found from experiments, positively framed decision scenarios for business investment led to different decisions when compared with negatively framed decision scenarios, even though the same value of income was expected from the business. Such framing bias is likely to be an important factor in decision-making under uncertainty [78]. In addition, rational analysis was found to be insufficient, while behavioral aspects were necessary to explain RE diffusion. Masini and Menichetti, through a questionnaire survey, found that decisions of RE investors were sensitive to personal beliefs regarding technical adequacy and institutional pressures from peers [63,64]. Salm et al. showed that investors occasionally relied on their “gut feeling” in RE investments [65]. West et al. analyzed the influence of cultural and ideological identities in RE investments using a focus group approach with cultural theory, taking an example of the South West UK, developing deeper understandings of how individuals’ worldviews can inform opinions and behavior in relation to RE. [66]. These studies indicate that the decisions made by RE investors, in reality, are not always normative, but are sometimes subjective, especially under uncertainty. As stated above, the conventional NPV approach is one useful method of evaluating the investments by a company, and the real options and prescriptive approach may compensate for the demerits of the NPV approach for decision making under uncertainty. However, these normative approaches do not express the non-normative perspectives of the decision-makers such as influences from personal beliefs, co-workers and competitors even though their importance has been recognized [63,64] .

As contrasted with the normative and prescriptive approaches, the descriptive approach focuses on clarifying or modeling how people make decisions in reality, including the non-normative perspective of decision-makers [41]. Prospect theory, which was developed by Kahneman and Tversky based on behavioral economics, is representative of the descriptive approach. The theory claims that preferences of decision makers in reality are reference-dependent and exhibit loss aversion, and probabilities are subjectively weighted from the non-normative decision making point of view [46,47]. Some studies have applied prospect theory to the field of energy investment. Klein et al. analyzed household investment in solar photovoltaics in Germany based on prospect theory [67]. Heutel examined individuals` behavior and its impacts on investments in energy saving in the US and suggested that the impact of prospect theory on a policy may be substantial [68]. Although these studies considered non-normative decisions, they did not focus on the company's decision making for RE investments. Other studies have focused on behavioral decisions for RE investments including non-normative aspects of people`s and company's decisions. However, these studies are mostly based on the analysis of questionnaire surveys or qualitative analysis [63–66]. As stated above, previous studies have not attempted to quantify the values of RE investments from both normative and non-normative perspectives, particularly regarding the decision-making process of power generation companies to invest in large-scale RE ("RE companies" hereafter). Therefore, we infer that conventional normative and prescriptive approaches will be insufficient when governments formulate future policies and design mechanisms for the large-scale introduction of RE under uncertainty, and that a new approach that quantifies the non-normative decisions of RE companies is therefore necessary.

This work infers that the conventional normative approaches will be insufficient when governments formulate future policies and design mechanisms for the large-scale introduction of RE under uncertainty, and a new approach that quantifies the non-normative decisions of RE companies is necessary.

1.2.3 Environmental management

Environmental management is an important element with relation to decision-making for emissions reduction and energy transitions. Many companies have achieved certification for ISO 14001: 2015 [79], which specifies the requirements for an environmental management system and focuses on the environmental performance of an organization, environmental management has become one of the most important topics for a company's operation. Suppose an effort for the energy transition of companies is interrupted as a part of environmental management. In that case, the impact on a company's financial performance brought by environmental management becomes a subject of this study's interest.

When the correlation between environmental management and financial performance is discussed, there is a fundamental question: "Do strict environmental regulations make companies less competitive?" Porter answered "No" to this question [80], which became known as the so-called Porter hypothesis. Porter and Linde claim (based on an investigation of literature and the experiences of some American companies) that properly designed environmental regulations encourage companies to re-engineer their technologies, and that the innovation of technologies could offset the cost of complying with the regulations [81]. On the other hand, Palmer et al. argued against the claims of Porter and Linde. They contend that environmental regulations result in reducing profits of regulated companies even though incentives are given [82]. They also state that each regulation's economic attractiveness should be evaluated by the benefits and costs [82].

Although it is apparent that no consensus on whether environmental management brings financial benefit has been formed yet, there have been several subsequent studies that focus on a company's environmental management in the field of financial and management analysis. For example, Russo [83] et al. analyzed the profitability and growth of 243 companies using a unique environmental index and found that the higher the industry growth rate, the stronger the positive correlation between environmental performance and profitability. Konar et al. [84] clarified the correlation between environmental performance and corporate performance of U.S. S&P 500 companies. The results showed that improving environmental performance increased the market value of a company, and each industry had different features. Waddock et al. [85] pointed out that a specific CSR index showed a positive correlation with financial performance in the US market in the 1990's from the Environment, Society, and Governance (ESG) point of view. Zhao et al. [86] re-examined Waddock's study based on the latest data, they demonstrated that ESG would not necessarily lead to good financial performance. Within the context of the Japan, some research has analyzed the relationship between SCR/ESG and financial performance of companies in the Japanese market. For example, Ariu et al. [87] examined the relationship between cooperate social responsibility (CSR) evaluation and corporate financial evaluation of Japanese companies. They found that larger companies were more likely to improve their CSR activities and that corporate governance could harm profitability and safety. Endo [88] examined companies listed on the First Section of the Tokyo Stock Exchange, and he showed a positive correlation between the social performance and the company's value.

However, most previous studies have focused on the correlation between corporate environmental management/social responsibility and financial performance. There are no studies that have attempted to identify the characteristics of companies that are proactive in de-carbonization and energy transition from financial and managerial analysis perspectives, specifically in the Japanese market.

1.3 Aim of the work

As mentioned in Section 1.2, this work tries to address the insufficiency of past quantitative system modeling in order to examine the energy transition from the company's point of view. Concretely, as per the literature review, the chronological strategies of replacement and abolishment of retiring power plants should be considered in the energy transition period based on quantitative system modeling (Section 1.2.1). Regarding decision-making in RE investments, few studies attempt to quantify not only the normative decisions but also the non-normative decisions of RE investment companies (Section 1.2.2). Besides, to observe the outcomes of the company's efforts on past and ongoing energy transition, it is important to identify the characteristics of proactive companies in de-carbonization and energy transition from financial and managerial analysis perspectives. (Section 1.2.3).

Therefore, this work sets the aim to clarify the conditions that move companies forward in the energy transition under restrictions of existing infrastructure with multiple perspectives based on quantitative approaches: both macroscopic and microscopic, technological/economic and psychological, normative and non-normative perspectives, with the case study of Japan and selected sub-regions. The novelty of this work is in the proposal and application of a new combination of existing methods to examine companies' energy transition from multiple perspectives under constraints of existing infrastructure. Besides, this study hypothesizes that the effective use of existing power generation facilities and renewable energy potential in each region will be a key factor in encouraging companies to introduce large-scale renewable energy.

To examine the hypothesis and interpret the results of this work, it is necessary to clarify how the transition from fossil fuel to RE can maintain “desirable” conditions for society and companies. Starting with, "what is desirable?”

First, since this work mainly considers companies related to electricity and RE investments, a stable balance between energy supply and demand should be one of society's constraints. Second, since the current transition is from fossil fuel to RE, consistency with the global decarbonization scenarios such as the Paris agreement should be another constraint. Third, the profits and costs of the transition should be economically affordable. In addition to these fundamental conditions, as McCauley introduces, the transition must consider “energy justice” to ensure policies and programs guaranteeing equitable access to resources and technologies [89]. Though there are various aspects of energy justice, it is summarized as distribution justice, recognition justice, and procedural justice; with justice, outcomes of the transition should be distributed, the influence of the outcomes should be recognized, and the process leading to the outcomes should be fair [89]. These justices should also be among the desirable conditions or criteria. Besides, with regard to companies, the Davos manifest says that “the purpose of a company is to engage all its stakeholders in shared and sustained value creation. In creating such value, a company serves not only its shareholders but all its stakeholders – employees, customers, suppliers, local communities, and society at large [90].” That is, the transition should be affordable not only for shareholders but also for other stakeholders such as employees and suppliers. Given the statements above, this study defines the desirable conditions for the energy transition as follows.

For society (Macroscopic);

S-1. A stable balance between supply and demand can be achieved. [Constraint]
S-2. Consistent with the global de-carbonization scenarios. [Constraint]
S-3. Affordable economic burden. [Distribution justice]
S-4. Sufficient and equitable energy accessibility. [Distribution justice]

For a company (Microscopic) and companies (Meso-scale);

C-1. Keep sufficient profits or avoid critical losses.

C-2. Acceptable changes in employment and supply chain.

C-3. Well-deserved recognition of efforts to the transition.

where, the level between macroscopic and microscopic is called "Meso-scale" in this study, which describes some aggregates of companies or industrial sectors.

In order to discuss these desirable conditions and lead to conclusions on this work, a novel framework is designed, which expresses multiple perspectives for the energy transition of companies with quantitative approaches, as shown in **Figure 1.3**. Chapters 2, 3, and 4 of this work are allocated to a part of the framework considering Japan and some of its subregions. Besides, **Figure 1.4** shows the scope of this work, including the domain, regions, and timeframe of each study.

Chapter 2, addresses the macroscopic perspective, and aims to analyze the impact of various scenarios for the replacement and abolishment of existing power generation facilities and clarify the preferable pathway of the energy mix to a 100% RE society while minimizing the total cost of power generation and facilities. This chapter focuses on the power supply system in Western Japan with the timeframe from the 2020s to 2050s, and the target of zero CO_2 emissions from electricity expected to be achieved by the 2050s.

Chapter 3 focuses on the non-normative perspective of RE investment in addition to the normative perspective. A novel framework is designed that incorporates both the normative and non-normative decision-making perspectives of RE companies to describe the investment behavior observed in reality. This chapter aims to obtain novel information on the decision-making behavior of RE companies under uncertainty in the energy market, which is not yielded by the conventional NPV approach. The constraints, such as existing infrastructure, should be consistent with those of Chapter 2. In this chapter, a decision-making model of a RE investment company in the energy market of the Kansai area is developed, and the decisions for 30-years of investments in RE are examined.

Chapter 4 attempts to observe and overview how companies' past efforts in the energy transition affect the current situation of companies from the meso-scale perspective, which is subject to influence by results of both macroscopic and microscopic perspectives. This chapter aims to extract the characteristics of companies that are proactively shifting to RE by quantitively analyzing management information and CO_2 emissions. The results of the analysis are expected to bring new knowledge on the energy transition of companies. This chapter aims to extract the characteristics of companies listed on the First Section of the Tokyo Stock Exchange (TSE) that are proactively shifting to RE by quantitively analyzing management information and CO_2 emissions as of 2019.

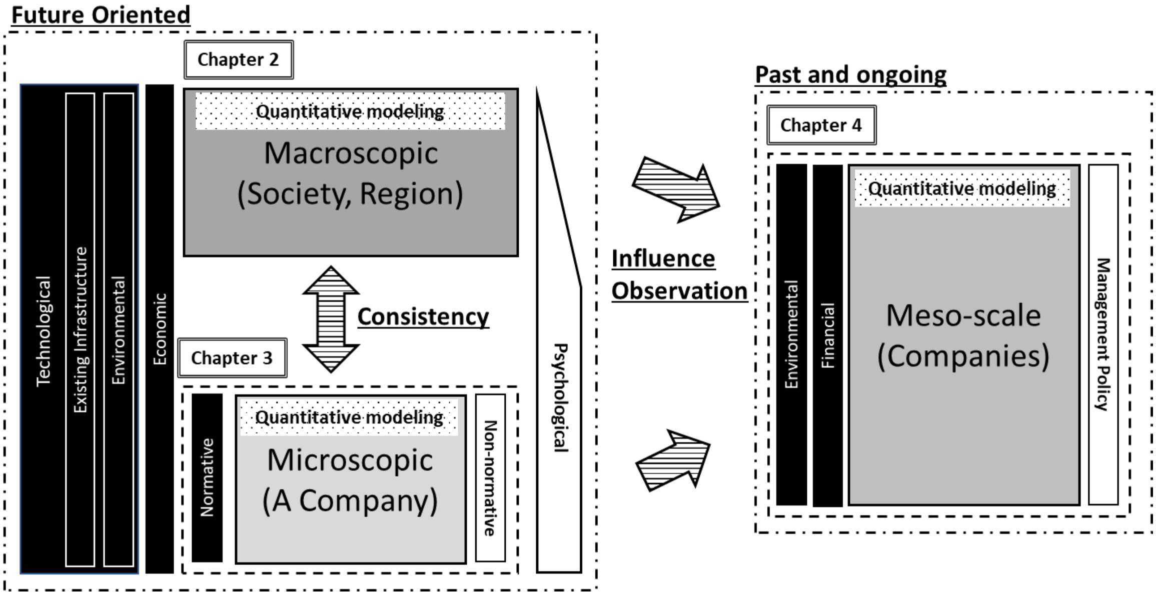


Figure 1.3 Framework of the study, which expresses multiple perspectives for the energy transition of companies.

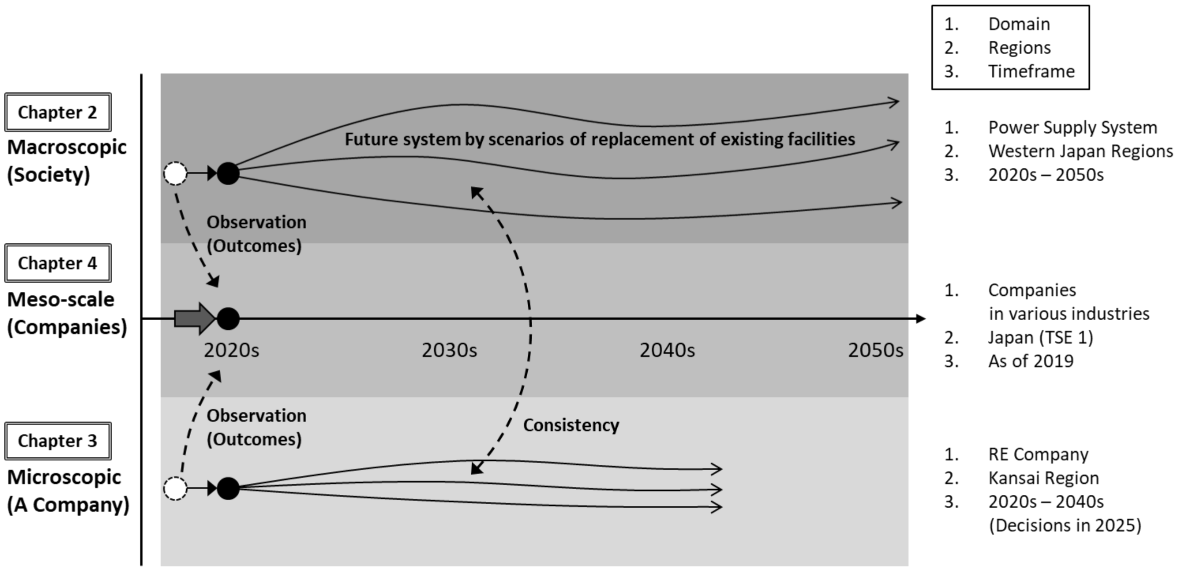


Figure 1.4. Scope of this work

1.4 Contribution of this work

This work aims to clarify how to move companies forward in the energy transition from fossil fuel to RE under restrictions of existing infrastructure with multiple perspectives based on quantitative approaches. As Section 1.2 introduced, little previous literature has attempted to provide quantitative outcomes of a company's contribution to the energy transition from both normative and non-normative aspects considering the constraints of existing infrastructure. This work will contribute to providing new knowledge on companies` energy transitions based on quantitative analysis and provide suggestions for future policy-making on the energy transition.

This work proposes two novel frameworks and four quantitative models to discuss the work's aim. Section 1.3 designs the framework, which expresses multiple perspectives for the energy transition of companies, and the possibilities of companies' energy transition are discussed based on the framework in Chapter 5. Chapter 2 presents a model which describes technologies, energy flows, and inter-regional energy transportation under constraints of existing infrastructure. Chapter 3 proposes a novel framework and decision-making model for companies that invest in large-scale RE. Chapter 4 uses two quantitative approaches to analyze financial performance, CO_2 emissions, and management policies of companies. Although this work applies the frameworks and models to Japan and subregions, these frameworks and models can be expanded to other regions and countries and be practically expected to contribute an analysis of the energy transition.

CHAPTER 2. Power Supply System for Large Scale Renewable Energy Introduction under Different Strategies of Existing Power Plant Replacement

2.1 Introduction

This chapter represents the macroscopic perspective of the energy transition. This study seeks to clarify the impact of replacing and abolishing existing power generation facilities for the pathway to the energy transitions based on the detailed technical properties of power generation facilities.

As introduced in Section 1.2.1, there are several studies on the future energy mix and energy storage in Japan based on quantitative system modeling approaches. However, in the previous studies, the capacity of thermal power plants was usually determined endogenously or given in a single scenario. On the other hand, it is known that sites suitable for thermal power plants are limited in Japan, and it takes about ten years from the planning to the commercial operation of thermal power plants [91], which will be capable of 40 years of operation [92]. That is, existing power plants can constrain the future electricity supply and demand system, and the problem of previous studies seems to lie in the fact that restrictions of existing power plants have not fully been considered. Therefore, the chronological strategies of replacing and abolishing retiring power plants could be a key factor for the optimal energy mix in the future. It is crucial to clarify how the different strategies work.

In this study, the total cost of power generation in Western Japan is minimized under various scenarios to replace and abolish existing power generation facilities in the 2020s, 2030s, 2040s, and 2050s under the constraint of CO_2 emissions. This study aims to analyze the impact of the scenarios and clarify the preferable pathway of the energy mix to a 100% RE society.

2.2 Methodology

2.2.1 Overview of the Developed Model

Though this study focuses on the chronological replacement and abolishment strategies of existing power generation facilities during energy transition to RE, there are regional differences in the installation potential of RE and the combination of existing power generation sources. In order to express these regional differences, two regions were selected for analysis: the Kansai region, with its small RE potential and large natural gas-fired power generation capacity; and, the combined Chugoku, Shikoku, and Kyushu regions, with their high RE potential and large coal-fired power generation capacity. One of the features of this study is that each region has its own scenarios on the replacement and abolishment strategies of existing power generation facilities in the area. (See Section 2.2.3 for more details on the scenario.)

Additionally, hydrogen, which was considered to be generated by surplus electricity of RE, was applied as one of the energy storage technologies to effectively utilize the existing thermal power plants during large-scale RE introduction. The model was designed to enable hydrogen to be transported to other regions for consumption as well as for consumption within the region where it was produced.

This study developed a linear programming (LP) model to calculate the facility capacity, hourly energy output, consumption, and storage, giving a minimum total cost under various constraints in the facility configuration shown in **Figure 2.1**. GAMS, which is a versatile software for mathematical optimization, was used to calculate the optimal solution using the linear programming method. The definitions and formulations of the symbols and models used in this chapter are summarized in Appendix A.1.

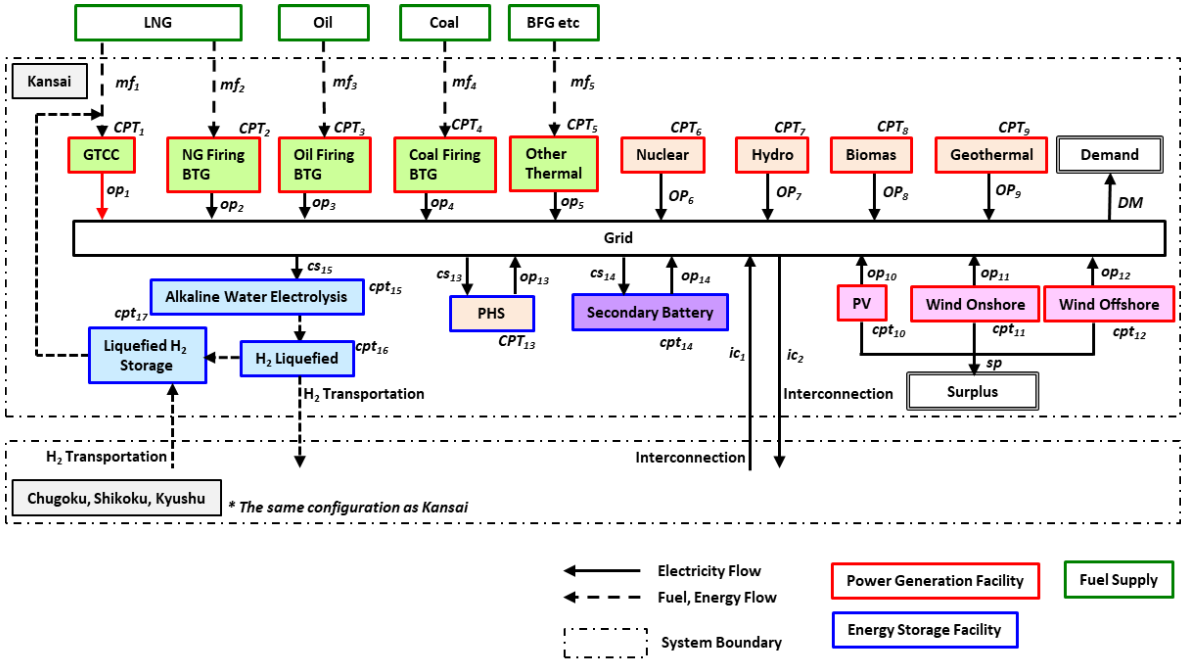


Figure 2.1. Overview of the model, which describes technologies, energy flow, and inter-regional energy transportation. Abbreviations in the figure show; GTCC: Gas turbine combined cycle, BFG: Blast Furnace Gas, PHS: Pumped Hydro Storage, and PV: Photovoltaics. Other nomenclature such as op and CPT in the figure is defined in the formulation of Appendix A.1.

2.2.2 Conditions for the analysis

(1) Scope of the analysis

As described in Section 2.2.1, the western part of Japan was divided into the Kansai region and the Chugoku, Shikoku, and Kyushu region. In the following sections, "Chugoku, Shikoku, and Kyushu" refers to the sum of the Chugoku, Shikoku, and Kyushu region.

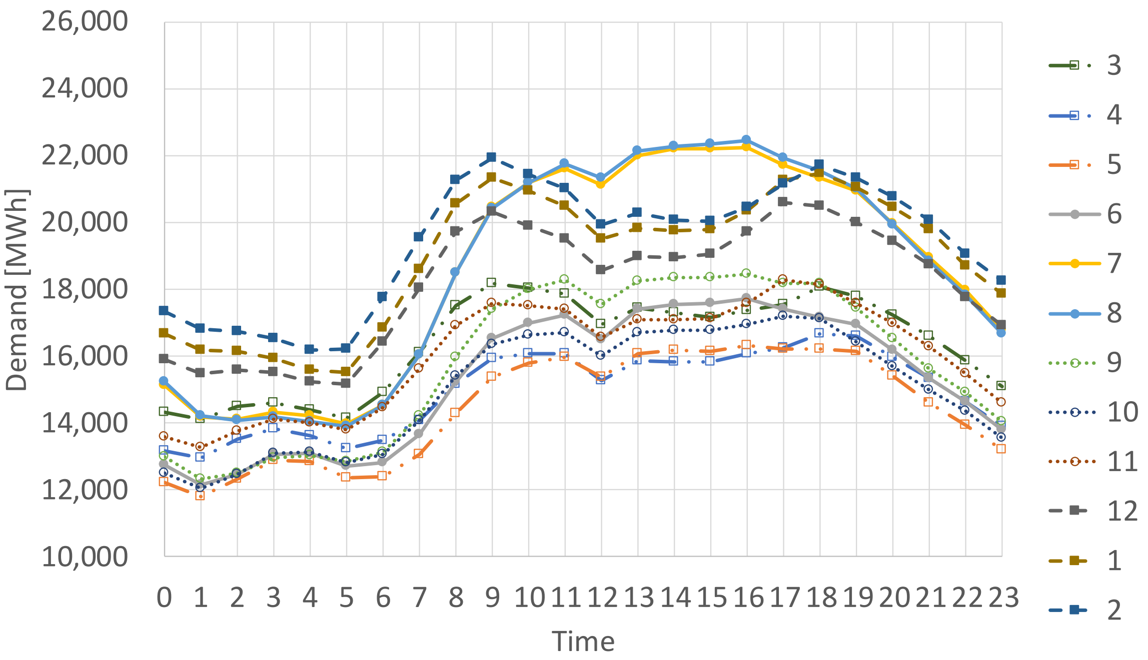
The analysis period was one year each in 2017, the 2020s, 2030s, 2040s, and 2050s, and the analysis was carried out in chronological order up to the 2050s. The single-year optimal solution given by the LP model in the previous year was succeeded by the cost minimization calculation in the next year. It should be noted that the optimal solution of each decade by this time-series approach may be different from one by dynamic programming. However, the time-series approach is expected to be appropriate since the investors of power generation facilities cannot predict decades-long optimal decisions in reality, and the replacement and abolishment strategies of existing power generation facilities are set up chronologically.

The time resolution of analysis was set to one hour in this study. Although shorter time resolutions yield more accurate results, it was shown that the optimal installed capacity for PV was equivalent between a time resolution of 10 minutes and one hour [93]. Besides, the recorded actual data were used for exogenous values in the calculation of 2017. The equipment specifications of the applied technologies are shown in Appendix A.2.

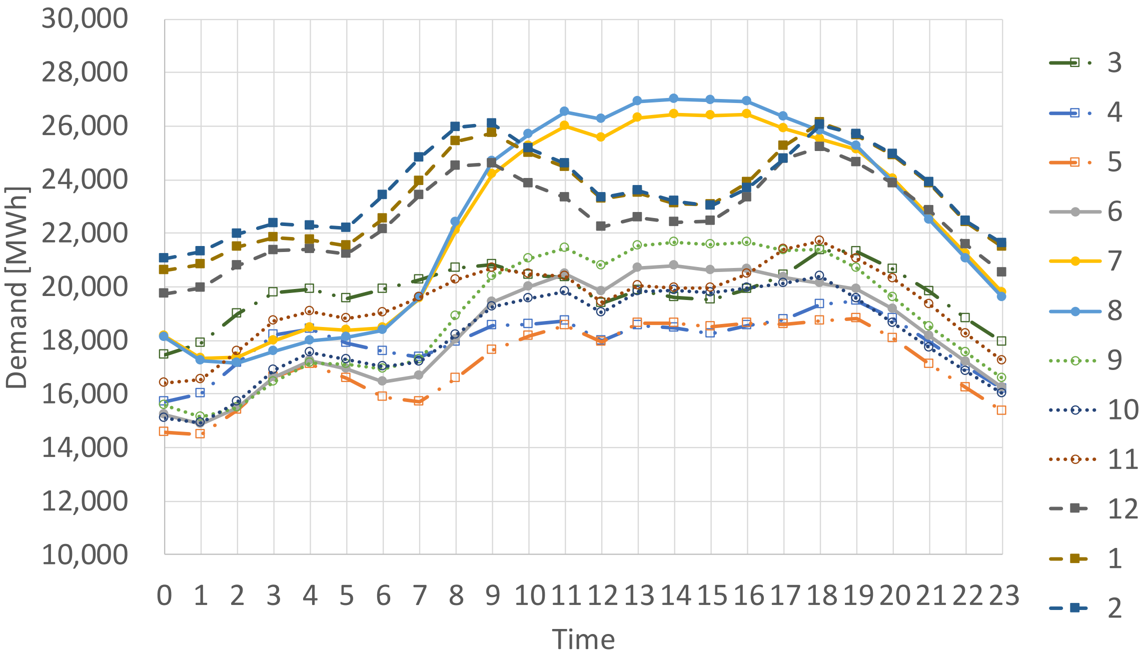
(2) Electricity demand

The electricity demand was based on the hourly “area demand” of the fiscal year 2017 (FY 2017) published by the Japanese electric power utilities (Kansai Electric Power, Chugoku Electric Power, Shikoku Electric Power, and Kyushu Electric Power) in accordance with the guideline by Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry [94–97]. It should be noted that the data does not include the self-consumption of PV in each region. However, the self-consumption rate of each month was about 6%-11% in the Kansai region and about 3%-15% in the Chugoku, Shikoku, and Kyushu regions compared to the installed solar capacity [98], and it is regarded as a sufficiently small amount in relation to the overall demand.

The electrical demand of FY 2017 was applied to each decade in this study since future electricity demand should have both increase and decrease perspectives; one is a decrease in demand due to energy saving, higher efficiency, and population reduction. The other is an increase in demand due to the higher electrification rate of energy consumption in the industrial, consumer, and transportation sectors. As for the electricity demand trend, the demand is great in July and August (summer) and January and February (winter) in both the Kansai region and the Chugoku, Shikoku, and Kyushu regions. Also, it is typically observed that summer demand peaks from daytime to evening, and winter demand peaks in the morning and evening, as shown in **Figure 2.2**.



(a)



(b)

Figure 2.2. Average monthly electrical demand of each region in FY 2017: **(a)** Kansai region and **(b)** Chugoku, Shikoku, and Kyushu region, numbers on the right side of the figure show corresponding months.

(3) Thermal power generation

The thermal power generation facilities included steam power (coal, oil, and natural gas), gas turbine combined cycle (GTCC), and other gas-fired (by-product gas fired) power generation systems.

GTCC was categorized into a firing temperature class of 1350 deg. C, 1400-1500 deg. C and the cutting-edge, and properties were set up for each technology. Other gas-fired thermal power plants mainly used by-product gas such as blast furnace gas (BFG) from iron mills, and the by-product gas was expected to be supplied to generators at no cost.

The capacity and operating hours of each facility was established as of 2017, referring to the information published by each power producer [99–104], and was used as a starting point for future plans for the renewal and closure of thermal power plants. In this study, the future capacity of thermal power plants was treated as a constraint for the planned renewal and decommissioning of thermal power plants, which was described in Section 2.2.3.

(4) Nuclear power generation

The capacity of the nuclear power generation facilities referred to the information published by each electric power utility, and the capacity factor was fixed at 80% [105,106]. In this study, the future capacity of a nuclear power plant was given by lifetime extension and abolishment scenarios, which were described in Section 2.2.3.

(5) Renewable Energy

Solar photovoltaic (PV), onshore wind power, offshore wind power, general hydraulic power, geothermal power, and biomass were selected as applied technologies. In this study, PV, onshore, and offshore wind power, in particular, were called Variable Renewable Energy (VRE). PV included both residential and mega-solar, and offshore wind consisted of both bottom-mounted and floating types. As for the biomass, only woody biomass firing was considered.

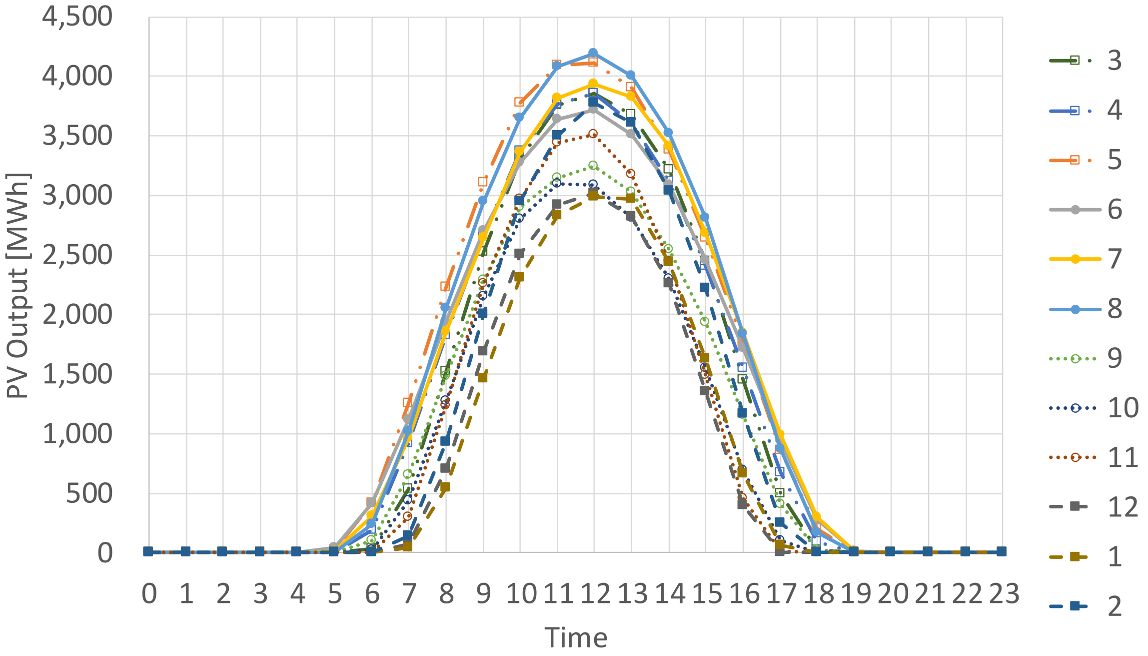
Figure 2.3 shows the average monthly PV and onshore wind output of the Kansai region at different times of the day. Although the amount of power generated differs according to the weather and other factors in the same month, the trend is that PV power generation surges in the morning and declines sharply in the evening. Besides, PV power generation is greater in July and August (summer) and smaller in January and February (winter). On the other hand, the variation in the amount of electricity generated by onshore wind is relatively small over time, generating more electricity in the winter and less in the summer. These trends of power generation are also true in the Chugoku, Shikoku, and Kyushu region.

The trends in hourly electricity generation (kWh) per equipment capacity (kW) of PV and onshore wind power were configured referring to the historical data of FY 2017, which were published by the electric utility companies in each region [94–97], as well as electricity demand defined in Sec.2.2.2 (2). Since hourly historical data for offshore wind was very limited, the trend in hourly electricity generation of offshore wind was assumed to be the same as that of onshore. The power output per unit of offshore wind facility was set to be 1.5 times that of onshore wind considering the capacity factors of offshore and onshore wind were 30% and 20% [92], respectively. The actual power output of VRE varies depending on various factors such as weather, topography, shielding of the equipment however, this study applied fixed hourly power output trends per equipment capacity in order to obtain practical results.

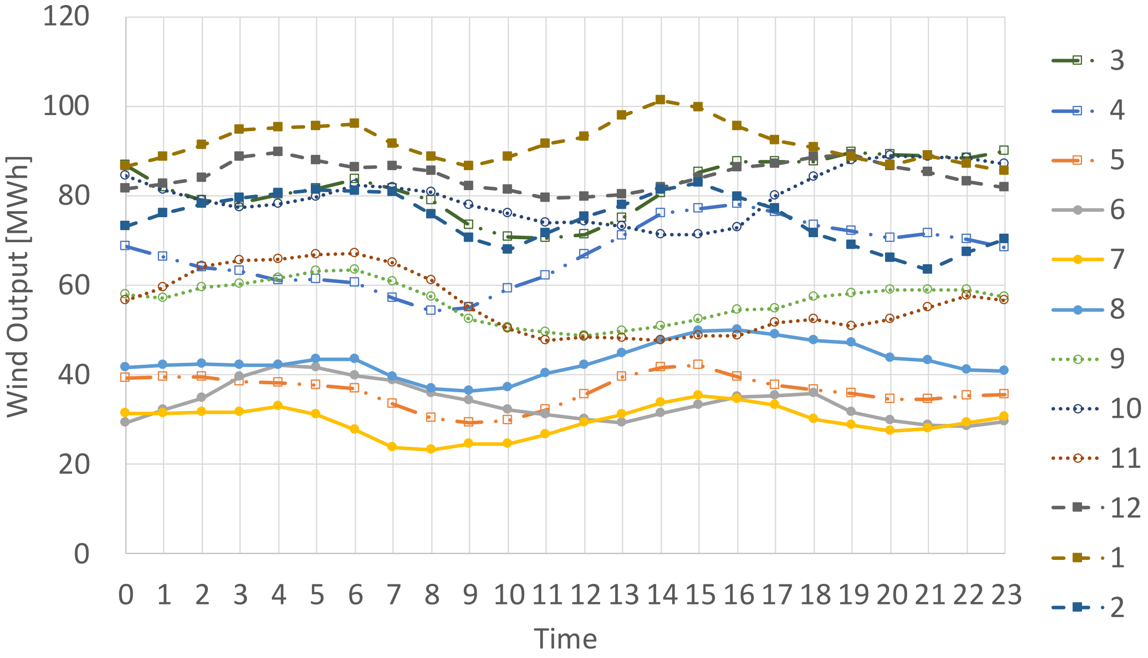
General hydropower was expected to maintain electricity generation as of 2017, and new construction of hydropower was not considered since there are no construction plans in the Kansai, Chugoku, Shikoku, and Kyushu region [107].. The future capacity of geothermal and biomass was defined exogenously as shown in **Table 2.1** considering the energy mix described by the Japanese government; the energy mix in 2030 was assumed to be 1.0%-1.1% for geothermal and 3.7%-4.6% for biomass against total power generation. The future capacity of geothermal and biomass were assumed to increase linearly, passing on 1.0% and 3.7%, respectively. However, since the Kansai region had negligible installation potential of geothermal, the capacity of geothermal in Kansai was set as 0 kW. Also, the biomass fuel cost was not included in the total cost because it was assumed that the fuel would be procured within the region.

Table 2.1. Expected capacity of geothermal and biomass power plants

Region	Type	Year / Capacity [MW]			
		2020	2030	2040	2050
Kansai	Geothermal	0	0	0	0
	Biomass	165	715	1,264	1,814
Chugoku, Shikoku, Kyushu	Geothermal	175	244	314	383
	Biomass	349	867	1,386	1,904



(a)



(b)

Figure 2.3. Average monthly VRE output of the Kansai region in FY 2017: **(a)** PV and **(b)** onshore wind, numbers in the right side of the figure show corresponding months.

(6) Energy storage

Secondary batteries, pumped-storage hydroelectricity (PHS), and hydrogen were selected as energy storage technologies. Lithium-ion batteries are assumed to be used as the secondary batteries, and the capacity is determined endogenously. For PHS, no new installations were considered, and the installed capacity is assumed to be unchanged from 2017.

The hydrogen was generated by alkaline water electrolysis using surplus electricity from RE sources, and hydrogen imported from overseas and derived from fossil fuels were not considered. Moreover, trade in an external hydrogen market was not taken account in the model. That is, the system of hydrogen supply and demand is also closed within the two regions. The produced hydrogen was liquefied and used as a fuel for the GTCC, and the hydrogen could be transported between the regions.

(7) Fuel prices

The cost of fuel for each fuel was set, as shown in **Table 2.2** [108], and the currency exchange rate was fixed at 1$=110¥.

Table 2.2. Expected Fuel Price

Fuel	Unit	Year / Price			
		2020	2030	2040	2050
LNG	[$/mmbtu]	10.2	10.5	10.6	10.6
Oil	[$/t]	448.9	696.3	822.2	940.7
Coal	[$/t]	76.4	85.0	87.0	89.0

2.2.3 Restrictions

(1) Supply-demand balance and interconnection

Balancing the supply and demand was one of the restrictions; electricity supply and demand should be equal in each region. Interconnection between the Kansai region and the Chugoku, Shikoku, and Kyushu region was incorporated in the model, and interconnection outside of these regions was not allowed in the model. It would perhaps have been ideal to consider the interconnection outside of these regions from the more detailed regional analysis viewpoint. However, in this study, the model was simplified to have two distinct regions: one with low RE potential and large natural gas-fired capacity (the Kansai regions) and the other with high RE potential and large coal-fired capacity (the Chugoku, Shikoku, and Kyushu region). The focus was on clarifying the impact of existing facility replacement scenarios on future power supply systems. Also, the simplification of interconnection helped to reduce the calculation load.

The regional interconnection capacity was assumed to be 2,780 MW from the Kansai region to Chugoku, Shikoku, and Kyushu region and 3,900 MW in the counter direction based on the record in 2018. The interconnecting capacity maintained the same in each decade. Although the actual regional interconnections should consider electricity flow and reserve margins, these constraints were not considered in this model for simplicity.

(2) CO_2 emissions

The constraints on CO_2 emissions for each decade are shown in **Table 2.3**. In 2015, electric power utilities in Japan voluntarily announced that the CO_2 emission factor should be reduced to 0.37 kg-CO_2/kWh by FY 2030 [109], which is consistent with the energy mix presented by the Japanese government as of 2015. Also, CO_2 emissions from the electric power sector reach approximately 40% of whole CO_2 emissions in Japan as of 2017 [20], and it was assumed that CO_2-free in the electric power sector should be realized by 2050 in order to achieve the government's target of 80% CO_2 reduction by 2050. As the note in **Table 2.3** shows, the CO_2 emissions of natural gas-fired GTCC satisfy the CO_2 restrictions in 2020 and 2030.

Table 2.3. Expected CO_2 intensity limits

	Year			
	2020	2030	2040	2050
Electricity CO_2 Intensity Limit [kg-CO_2/kWh)]	0.40	0.37	0.10	0.00

NOTE: CO_2 emissions of each type of thermal power plant are 0.32 kg-CO_2/kWh for a natural gas fired GTCC and 0.78 kg-CO_2/kWh for a coal-fired power plant, based on the properties in Appendix A.2.

(3) Thermal power generation

As for the thermal power generation facilities, existing facilities in each region were included in the model, and the retiring thermal power plants were considered to be either replaced or permanently closed. New construction of thermal power plants on green fields was not considered. This is because land suitable for installing thermal power plants is limited in terms of fuel procurement, environmental assessment, and permits in Japan, and capital investment can be minimized by utilizing existing equipment of thermal power plants in general. Upgrading retiring thermal power plants to oil-fired or coal-fired plants was not considered, due to the recent promotion of environmental awareness and expected restrictions on CO_2 emissions.

In this study, the following two scenarios were taken into consideration as constraints on the thermal power capacity (refer to Appendix A.2 for the properties of each technology).

Scenario T-1: Fully Replacing the retiring thermal power plants with GTCCs

In each decade, GTCCs and natural gas-fired steam power plants in operation for 40 years will be replaced with cutting-edge GTCCs to maintain their capacity. Coal-fired steam power plants close to LNG terminals or natural gas pipelines will also be replaced with cutting-edge GTCCs while maintaining their capacity, and the other coal-fired steam power plants are abolished. Oil fired and other gas-fired (by-product gas-fired) steam power plants are scrapped as well.

Scenario T-2: Abolishing all retiring thermal power plants

In each decade, all thermal power plants that have been in operation for 40 years are to be scrapped.

The capacity of each facility was set based on the above scenarios by referring to the press releases [99–104] of each electric utility company. The power plants subject to replacement or scrap in each decade were those that had been in operation for 40 years. (See Section 2.2.5, **Figure 2.4** for the specific capacity of each scenario.)

The co-firing of hydrogen with natural gas was assumed to be available for GTCCs, and the co-firing rate of hydrogen with natural gas was limited to 30% until 2020 and 100% after 2030.

(4) Nuclear power

The following two scenarios gave the capacity of nuclear power plants.

Scenario N-1: Life extension of retiring nuclear power plants

All nuclear power plants that have been authorized for restart or have obtained a permit for change in the installation license as of May 2019 [105] will be operated up to 60 years after the initial start of commercial operation. Nuclear power plants that have been in operation for 60 years will be scrapped.

Scenario N-2: Scrapping retiring nuclear power plants

Nuclear power plants will be decommissioned after 40 years of operation. However, only plants that have been licensed for 60 years of operation [106] as of May 2019 will be operated until 60 years after the start of commercial operation. In this scenario, all nuclear power plants will be decommissioned by the 2030s.

See **Figure 2.4** for the capacities of each scenario. Although some of the nuclear power plants may not be restarted at the timing of 2020, these plants were assumed to be in operation in this model since they most likely would be in operation in the early 2020s.

(5) Renewable Energy

As for VRE, the installed capacities should be less than the installation potential [110] of each region, which is shown in **Table 2.4**. The potential of PV included both residential and mega-solar, and that of offshore wind consisted of both bottom-mounted and floating types.

Table 2.4. Installation potential of VRE in each region

Region	Type	Installation Potential [MW]
Kansai	PV	39,310
	Wind Onshore	11,570
	Wind Offshore	30,220
Chugoku, Shikoku, Kyushu	PV	103,480
	Wind Onshore	30,380
	Wind Offshore	525,670

2.2.4 Objective Function

The total annual costs (sum of capital investment, maintenance, and fuel costs) for the two regions were minimized as an objective function for each decade, satisfying the conditions (Section 2.2.2) and restrictions (Section 2.2.3). See Appendix. A.1.2 for the details of the objective function.

2.2.5 Case Definition

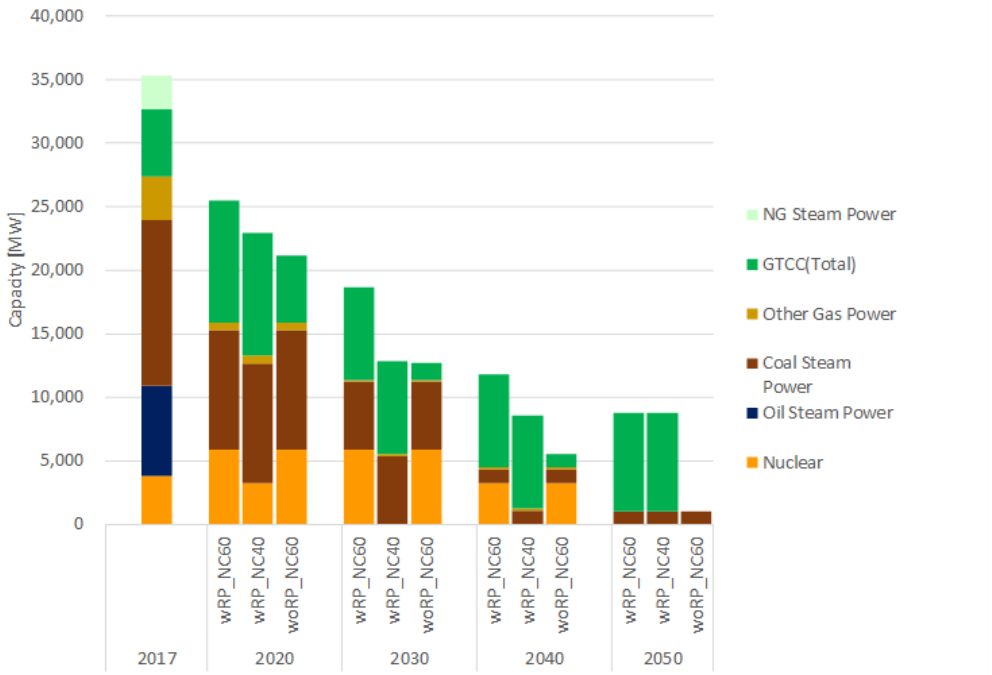
In this study, the three cases shown in **Table 2.5** were defined considering the thermal and nuclear power future scenarios set up in Section 2.2.3, and the optimal combination of power supply for the years 2020, 2030, 2040, and 2050, which minimized the total cost of each decade, were derived. In the case names, "wRP" means "with replacement" corresponding to the scenario T-1, "woRP" means "without replacement" to T-2, "NC60" means "nuclear operation for 60 years" to N-1, and "NC40" means "nuclear operation for 40 years" to N-2.

Figure 2.4 shows the total chronological capacity of thermal and nuclear power plants in each case. Since the Kansai region possesses a large number of existing natural gas-fired power plants and has coal-fired power plants located close to natural gas pipelines, the Kansai region has a high potential to maintain a large amount of total installed capacity subject to replacement to GTCC in the case of wRP_NC60 and wRP_NC40. On the other hand, for woRP_NC60, the total installed capacity at 2040 will be about half of what it was in 2017.

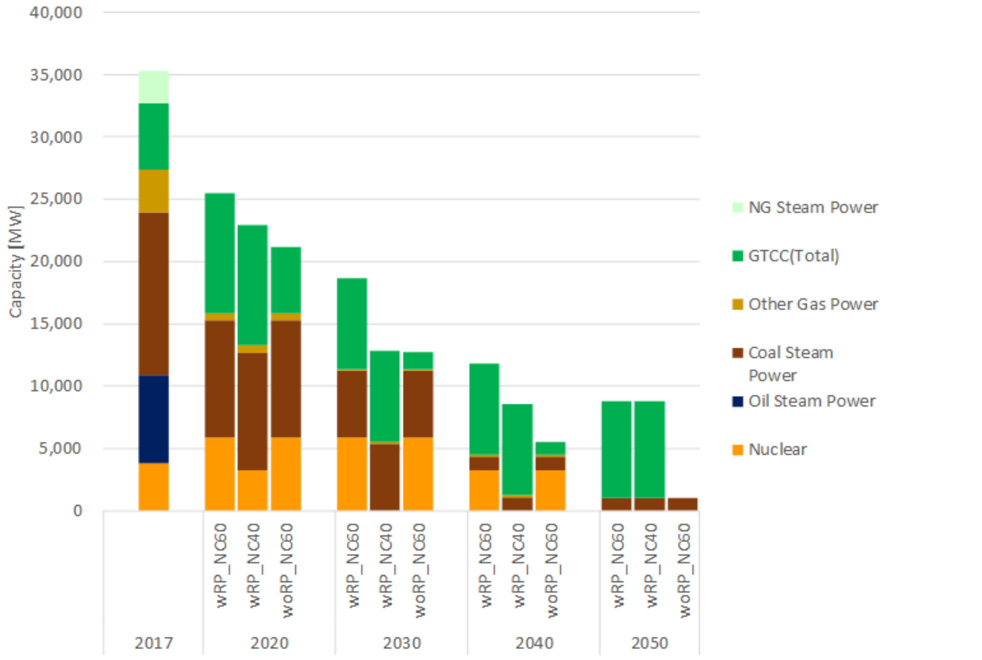
Since the Chugoku, Shikoku, and Kyushu region has a large number of coal-fired power plants and replaceable power plants are limited, this region's total installed capacity will gradually decrease toward 2040 in all cases.

Table 2.5. Developed cases of replacing and scrapping retiring power plants

Case Name	Thermal Power	Nuclear Power
wRP_NC60	T-1	N-1
wRP_NC40	T-1	N-2
woRP_NC60	T-2	N-1



(a)



(b)

Figure 2.4. Capacity of thermal and nuclear plants in each case: (a) Kansai region and (b) Chugoku, Shikoku, and Kyushu region.

2.3 Results

2.3.1 Combination of Power Generation Sources (the 2020s – 2040s)

Figure 2.5 and **Figure 2.6** show the capacities (MW) of the power generation and energy storage facilities that have been obtained as the optimal solution. The amount of power generation, the amount of power consumption, and surplus electricity (MWh) are shown in **Figure 2.7**, where positive values represent the amount of power supply, and negative values represent the amount of power consumption and surplus.

(1) The 2020s

The wRP_NC60 and wRP_NC40 in the Kansai region and the wRP_NC60 in the Chugoku, Shikoku, and Kyushu region showed only a slight increase in VRE. In contrast, the capacity of secondary batteries increased compared to 2017. This is because the batteries were charged during the night when demand was low, and the discharge of batteries supported the thermal power plant's output during the daytime and evening when demand was high. (See **Figure 2.8**, as an example.) In the case of wRP_N40 in the Kansai region, where retiring nuclear power plants were scrapped, the capacity of batteries installed was much larger than the other cases. The capacity of batteries, in this case, was equivalent to that of PHS; however, this scenario seemed not to be practical to install such large-capacity batteries in the 2020s. That is, this result implied that the retiring nuclear power should be utilized as long as possible in the 2020s in order to satisfy the CO_2 restriction.

In the case of the woRP_NC60, where thermal power plants were not replaced, onshore wind power and storage batteries were increased in both the Kansai region and the Chugoku, Shikoku, and Kyushu region. Onshore wind power and storage batteries were introduced to balance supply and demand and meet the CO_2 restrictions to compensate for the reduction in thermal capacity.

(2) The 2030s

The result of wRP_NC60 in the Kansai region showed a small increment in VRE but a large increase in batteries from the 2020s. This region had a large capacity of existing natural gas-fired power plants, and could satisfy the CO_2 restriction with little VRE introduction since the region could maintain the GTCC capacity by replacing the retiring plants and utilize the nuclear power plants for 60 years in this case. In other words, if the lifetime of nuclear plants were extended, the target CO_2 restriction of 0.37 kg-CO_2/kWh did not stimulate further VRE introduction. This implies that additional measures are necessary to expedite VRE introduction in this case.

In contrast, in the Chugoku, Shikoku, and Kyushu region, where the capacity of existing natural gas-fired facilities was less and coal-fired power plants are larger, onshore wind power capacity was about 25 times greater than in 2020 in order to meet the CO_2 restriction, even in the case of wRP_NC60.

In wRP_NC40 and woRP_NC60, the introduction of VREs in both the Kansai region and the Chugoku, Shikoku, and Kyushu region rapidly proceeded, accompanied by a decrease in the capacity of thermal and nuclear power plants. In particular, onshore wind power hit the maximum installation potential, and offshore wind power increased significantly. The decrease in thermal and nuclear power capacity in wRP_NC40 in the Kansai region and the Chugoku, Shikoku, and Kyushu region was 22% and 44%, respectively. On the other hand, the increase in VRE was 634% and 492%. That is, a substantial increase in VRE was observed as a measure to compensate for the decrease in thermal and nuclear power. In this case, wind power introduction proceeded ahead of PV. This is because the increase in solar power effectively covers the summer daytime demand peak, but it does not fully contribute to the winter evening demand peak.

The total capacity of thermal and nuclear power plants of wRP_NC40 and woRP_NC60 in both regions was almost the same in 2030. Still, the installed capacity of VRE in woRP_NC60 was 36% higher in the Kansai region and 11% higher in the Chugoku, Shikoku, and Kyushu region than that in wRP_NC40. Also, the electricity surplus in woRP_NC60 was more extensive than that in wRP_NC40. That is, when the same CO_2 restriction was given, the replacement to GTCC could promote VRE introduction efficiently compared to the lifetime extension of nuclear power plant; the output controllable power plants with low CO_2 emissions like GTCC were preferable to the fixed output power plants with no CO_2 emissions like nuclear, from the VRE introduction perspective.

(3) The 2040s

PV substantially increased in the Kansai region in all cases compared to the 2030s. This is because the Kansai region relatively maintained the large capacity of GTCC; PV output covered the demand for daytime during summer, and GTCC was used to meet demand in the evening. Therefore, PV was selected, which was more inexpensive than wind power, to satisfy the CO_2 restriction. **Figure 2.9** shows the electricity supply and demand balance of wRP_NC60 in the Kansai region in August 2040 as an example, and the trend stated above was observed in the figure. The other cases (wRP_NC40 and woRP_NC60) had the same trend.

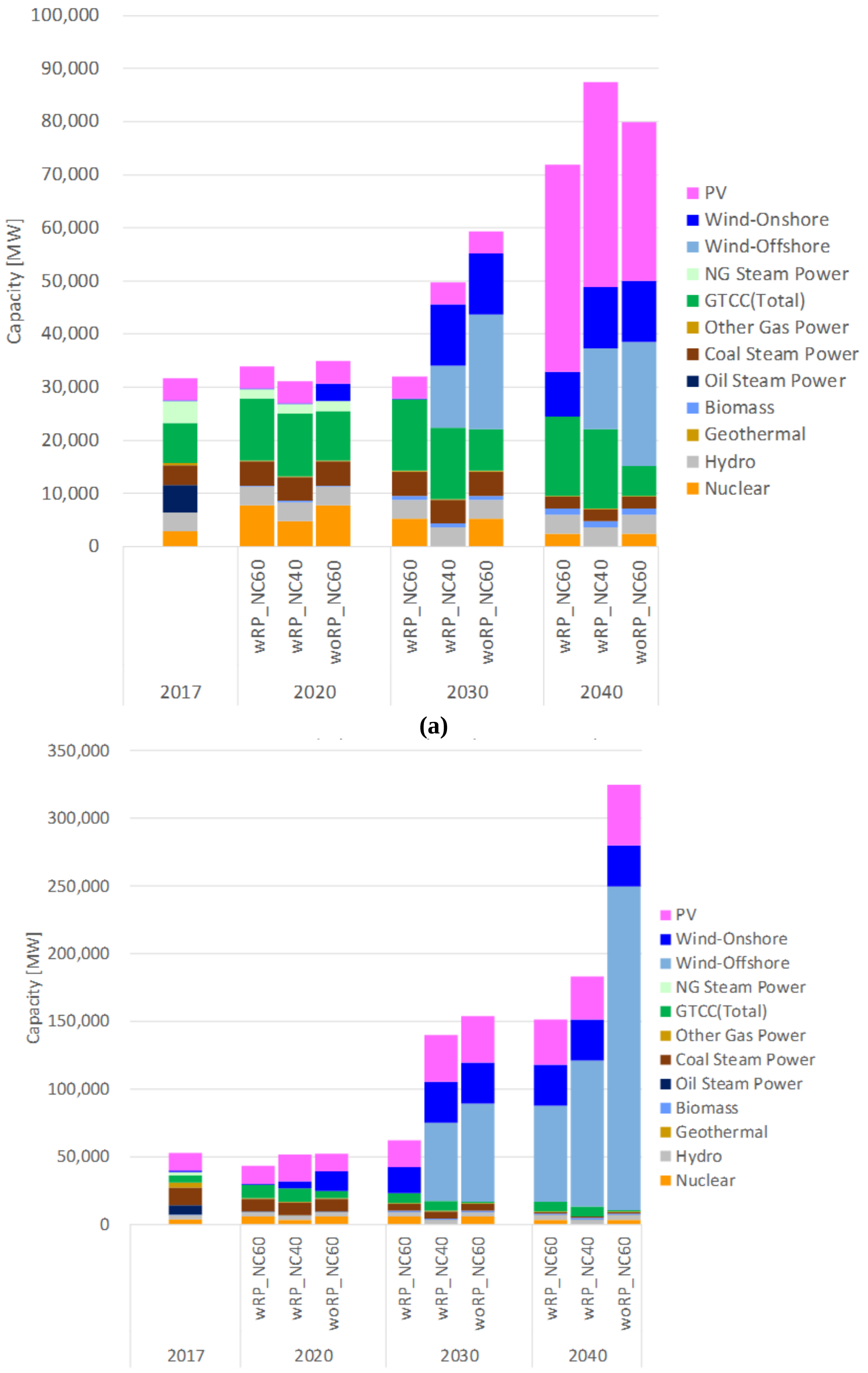
On the other hand, in the Chugoku, Shikoku, and Kyushu region, offshore wind power increase was more significant than the increase in solar power in all cases. Since the capacity of GTCC in the region was small, the peak demand in the winter evening needed to be covered by wind power, whose power generation has a low correlation with time of day. **Figure 2.10** shows the electricity supply and demand balance of wRP_NC60 in the region in February 2041 as an example, and the trend stated above was observed in the figure. The other cases (wRP_NC40 and woRP_NC60) had the same trend as well.

The results showed that when RE was introduced in a large quantity under the restrictions on replacing existing facilities, PV would increase ahead of wind power in the region where natural gas-fired power generation capacity was large. In contrast, wind power would increase ahead of PV in the region where natural gas-fired power generation capacity was small.

In 2040, the hydrogen generation for energy storage was introduced in the case of wRP_NC60 and wRP_NC40 as the optimal energy configuration; hydrogen was generated in the Chugoku, Shikoku, and Kyushu region, where the introduced VRE was larger (electricity surplus was more), and the hydrogen was transferred to GTCCs in the Kansai region. **Figure 2.11** shows the discharge from the energy storage of wRP_NC60 in the Kansai region in August 2040. It was observed that the batteries covered the peak demand while hydrogen-fired GTCC was maintaining a constant output. This result well expressed the characteristics of batteries and hydrogen-fired GTCC; the batteries have a limit on the maximum output duration for the capacity of the facility, and the hydrogen-fired GTCC can maintain a constant output as long as hydrogen is supplied.

In woRP_NC60, no hydrogen generation was introduced, and the capacity of batteries was increased substantially compared to the 2030s, with 300% in the Kansai region and 142% in Chugoku, Shikoku, and Kyushu.

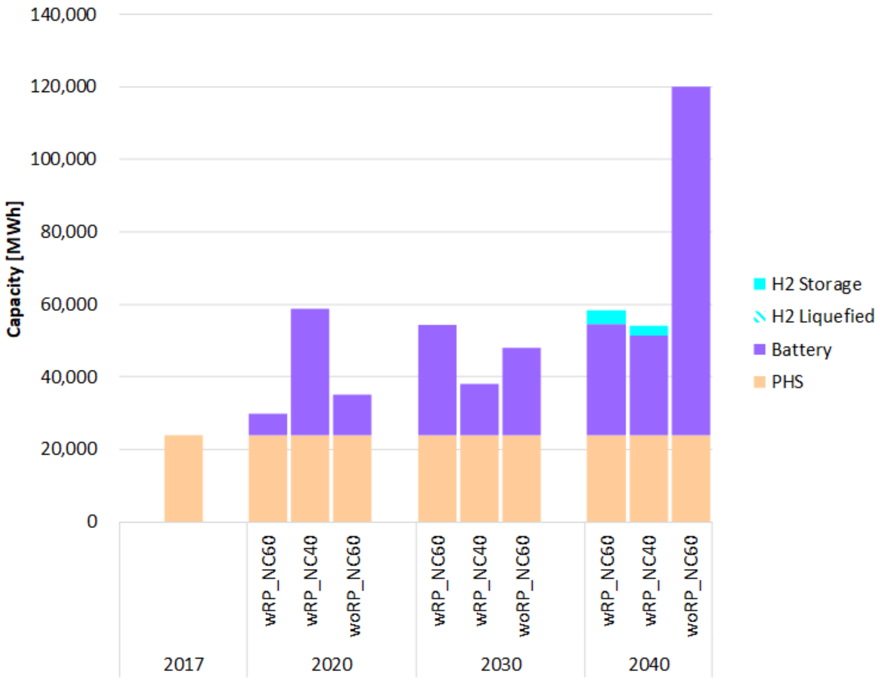
Furthermore, the same cost minimization calculation was executed without hydrogen energy technologies in 2040. The result was that the cost increased by about 5%/year for wRP_NC60 and about 2%/year for wRP_NC40 compared to the calculations with hydrogen technologies. That is, the possibility was shown to reduce the total cost by producing hydrogen with the surplus electricity in regions where many RE sources were introduced (the Chugoku, Shikoku, and Kyushu region) and transferring the hydrogen to regions where the GTCC capacity was relatively larger (the Kansai region).



(a)

(b)

Figure 2.5 Optimal capacity of power generation facilities in each case: **(a)** Kansai region and **(b)** Chugoku, Shikoku, and Kyushu region.



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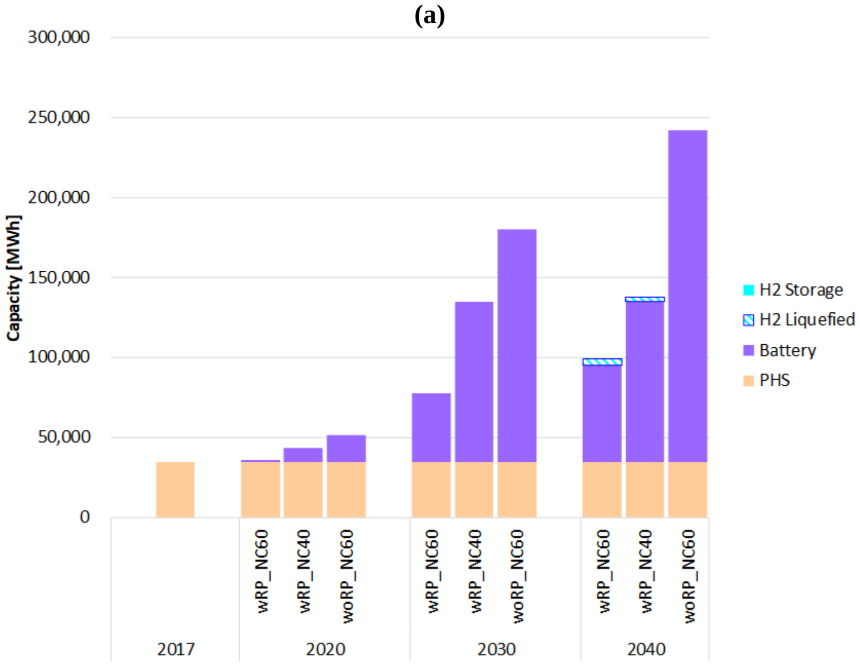


(b)

Figure 2.6. Optimal capacity of power storage facilities in each case: (a) Kansai region and (b) Chugoku, Shikoku, and Kyushu region.

Figure 2.7. Power discharge, consumption and surplus in each case: **(a)** Kansai region and **(b)** Chugoku, Shikoku, and Kyushu region.

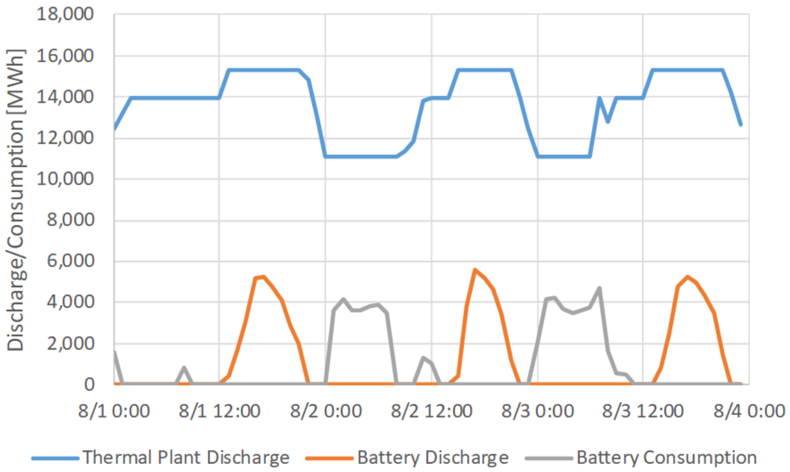


Figure 2.8. Calculation results of power discharge and consumption in the Kansai region from Aug. 1st to 3rd 2020 in case of wRP_NU40

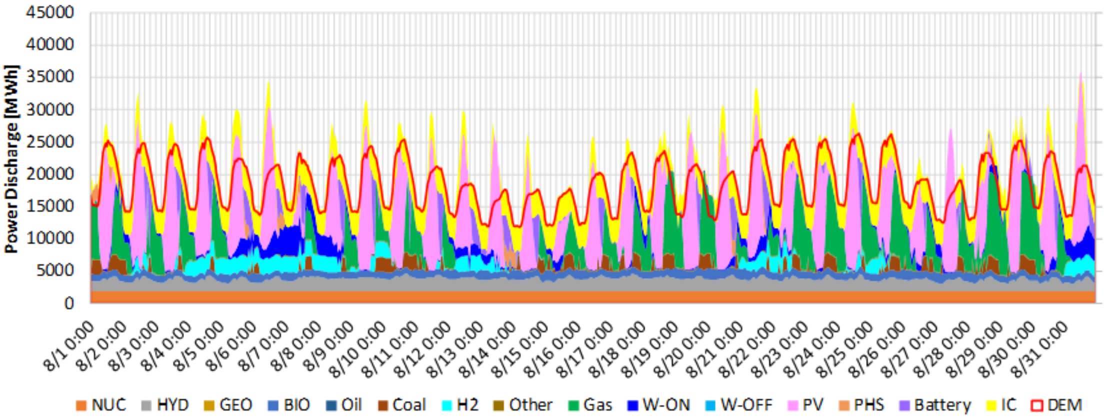


Figure 2.9. Electricity supply and demand balance of wRP_NC60 in the Kansai region in August 2040

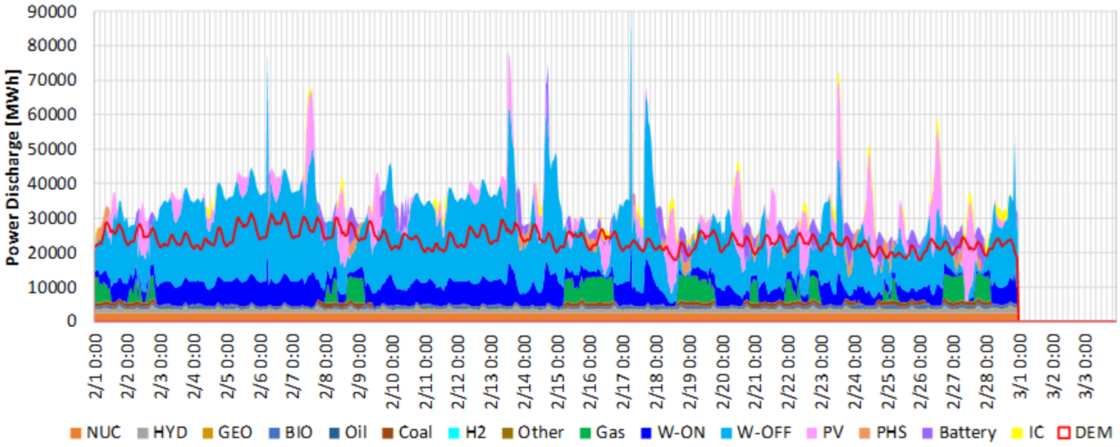


Figure 2.10. Electricity supply and demand balance of wRP_NC60 in the Chugoku, Shikoku, and Kyushu region in February 2041

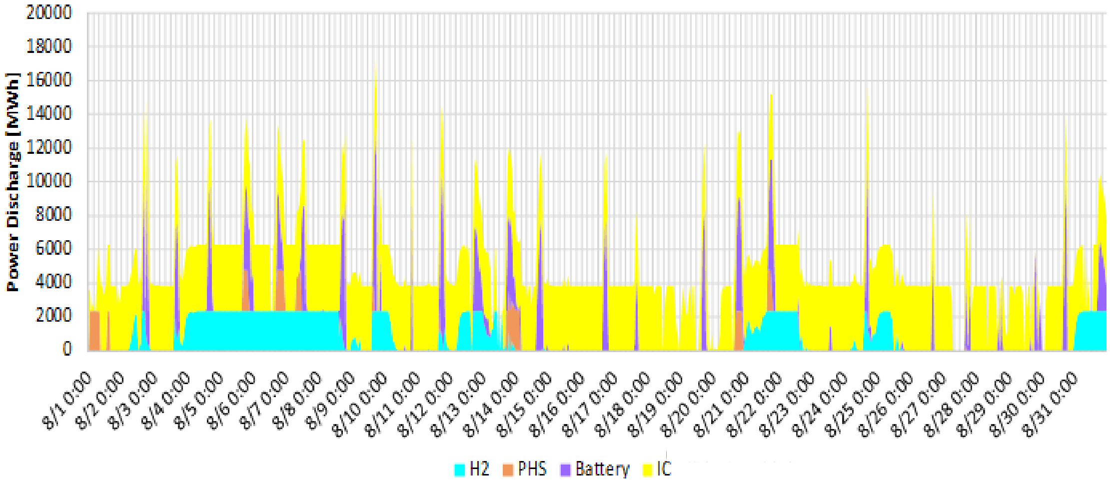


Figure 2.11. Discharge from energy storage of wRP_NC60 in the Kansai region in August 2040

2.3.2 Total Costs

Figures 2.12 and **2.13** show the total accumulated costs from 2020 to the 2030s (2020-2039) and 2020 to the 2040s (2020-2049), respectively. The labels in the figure are defined as follows;

- Thermal: capital investment (capital expenditure, CAPEX) and operation & maintenance (O&M) cost of thermal power plant facilities
- Fuel: fuel cost of thermal power plant facilities
- VRE: CAPEX and O&M cost of VRE
- ES: CAPEX and O&M cost of secondary batteries
- H2: CAPEX and O&M cost of hydrogen generation and storage facilities
- Others: O&M cost of nuclear facilities and PHS

In this chapter, the costs of each decade were obtained by multiplying the single-year costs calculated in accordance with the equation (A.1) in Appendix A by ten years. The total accumulated costs were the sum of the total costs for the 2020s and 2030s in **Figure 2.12**, and for the 2020s, 2030s, and 2040s in **Figure 2.13**. The total accumulated costs were nominal values that did not take price fluctuations into account.

As shown in **Figure 2.12**, the total accumulated costs over 20 years from 2020 to 2030s (2040-2039) were 89.7% for wRP_NC40and 33.6% for wRP_NC60, compared to that for woRP_NC60. In the case of wRR_NC60, the fuel cost still made up approximately half of the total cost. Since the difference in the total cost between wRP_NC60 and wRP_NC40 was relatively high, it was clear that the lifetime extension of nuclear power plants also contributed to cost reduction, in addition to the replacement of retiring thermal power plants in this timeframe.

In **Figure 2.13**, the total accumulated costs over 30 years from 2020 to 2040s (2040-2049) were 64.3% for wRP_NC40and 43.0% for wRP_NC60, compared to that for woRP_NC60. This means that the proactive replacement of existing thermal power plants could reduce accumulated total costs while introducing a large amount of RE. Based on the calculated cost and power generation of each scenario over the 30 years, the power generation costs were 13.0 yen/kWh for wRP_NC60, 19.5 yen/kWh for wRP_NC40, and 30.2 yen/kWh for woRP_NC40. It was found that the economic burden of wRP_NC40 and woRP_NC40 were very high compared to that of wRP_NC60.

In the Kansai region, the accumulated cost over the 30 years was 93.4% for wRP_NC40 and 62.25% for wRP_NC60 compared to that for woRP_NC60. In the Chugoku, Shikoku, and Kyushu region, the accumulated cost was 58.0% for wRP_NC40 and 38.8% for wRP_NC60 compared to that of woRP_NC60. That is, the replacement of existing thermal power plants contributed more to the total accumulated cost reduction of the Chugoku, Shikoku, and Kyushu region, where more VREs were installed, than in the Kansai region.

Here, the adequacy of the total accumulated cost for energy transition was examined by comparing it to the cost estimation for the energy transition in other investigations. **Figure 2.14** shows the comparison of total accumulated costs to other studies; the left side compares the total cost of each scenario to that of the World Energy Outlook (WEO) 2016 [111] from 2020 to 2039 (**Figure 2.14 (a)**). The right side compares to that of a report from 2017 by the World Wide Fund for Nature Japan (WWF) [112] for the period from 2020 to 2040 (**Figure 2.14 (b)**). The total cost only includes the CAPEX of thermal power plants and VRE, and the O&M costs are excluded. The original values given by WEO and WWF are the total cost of the whole of Japan from 2016 to 2040, and from 2010 to 2050, respectively. Therefore, the values were scaled to the cost of the Kansai, Chugoku, Shikoku, Kyushu regions from 2020 to 2040 and from 2020 to 2050 respectively in order to be consistent with the timeframes and regions of this study. The cost was adjusted by region using the ratio of electricity demand in the Kansai, Chugoku, Shikoku, and Kyushu regions to that in the whole of Japan as of 2017, which was approximately 0.35 [113]. The scenario of WEO is called “the New Policy Scenario,” which is consistent with the NDC of Japan for the Paris agreement, and that of WWF is a 100% renewable scenario which is expected to be 100% renewable society by 2050. The total accumulated costs of both scenarios do not include investments in technologies of energy storage.

As shown in **Figure 2.14 (a)**, although the investment cost of thermal power and VRE over the 20 years was 138% for wRP_NC60 compared to the WEO scenario, it was 774% for wRE_NC40 and 913% for woRE_NC60. That is, the necessary investments are significantly greater than WEO's scenarios in the case of wRE_NC40 and woRE_NC60.

On the other hand, **Figure 2.14(b)** shows that the investment costs of thermal power and VRE over the 30 years were 187% for wRP_NC60, 318% for wRP_NC40, and 531% for woRP_NC60 compared to the WWF scenario. Since the WWF scenario assumes that the energy demand in 2050 decreases in half from that in 2020, the investment costs should become relatively smaller than this study with fixed energy demand. Considering the difference in assumptions of the energy demand in 2050 between this study and the WWF scenario, the cost of wRP_NC60 was considered to be consistent with the WWF scenario; since the assumption of energy demand in the future of this study is twice that of WWF, the investment cost of approximately double may be in line with expectations. However, the investment costs for wRP_NC40 and woRP_NC60 were very large compared to that of the WWF scenario even when the difference in energy demand was accounted for.

Although conditions of WEO and WWF other than energy demand are also different from those of this study, it is expected that energy transition to RE with replacement of retiring thermal power plants and extending the lifetime of nuclear power plants is feasible from a macroscopic economic point of view.

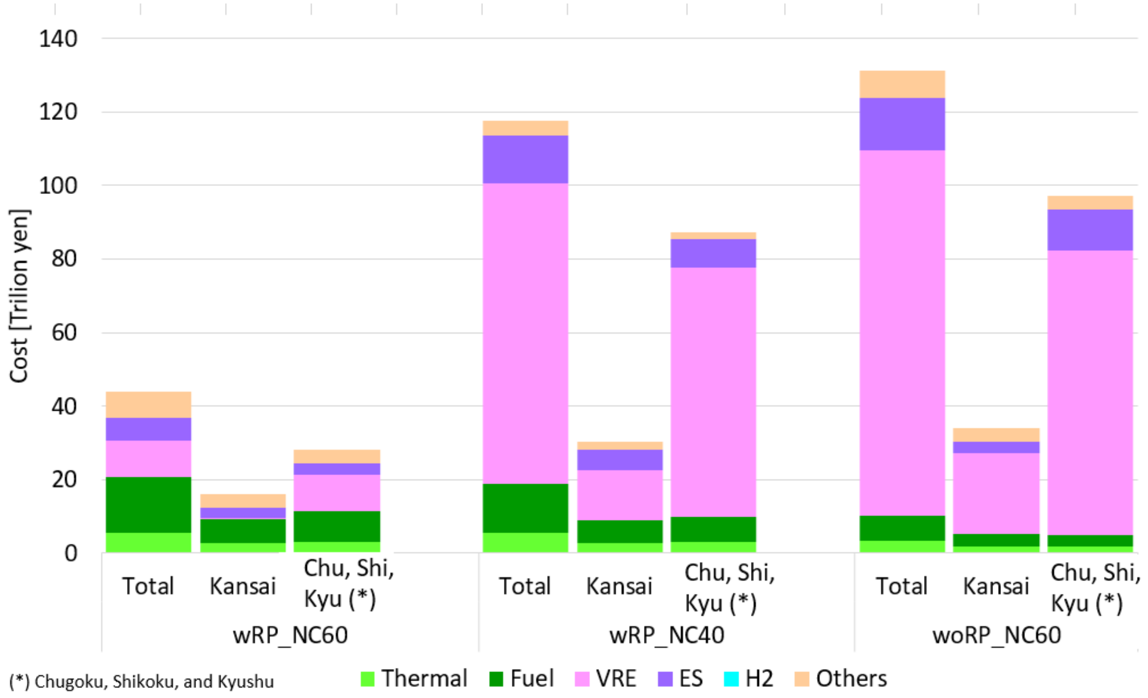


Figure 2.12. Total accumulated costs from the 2020s to 2030s (2020-2039) in each case

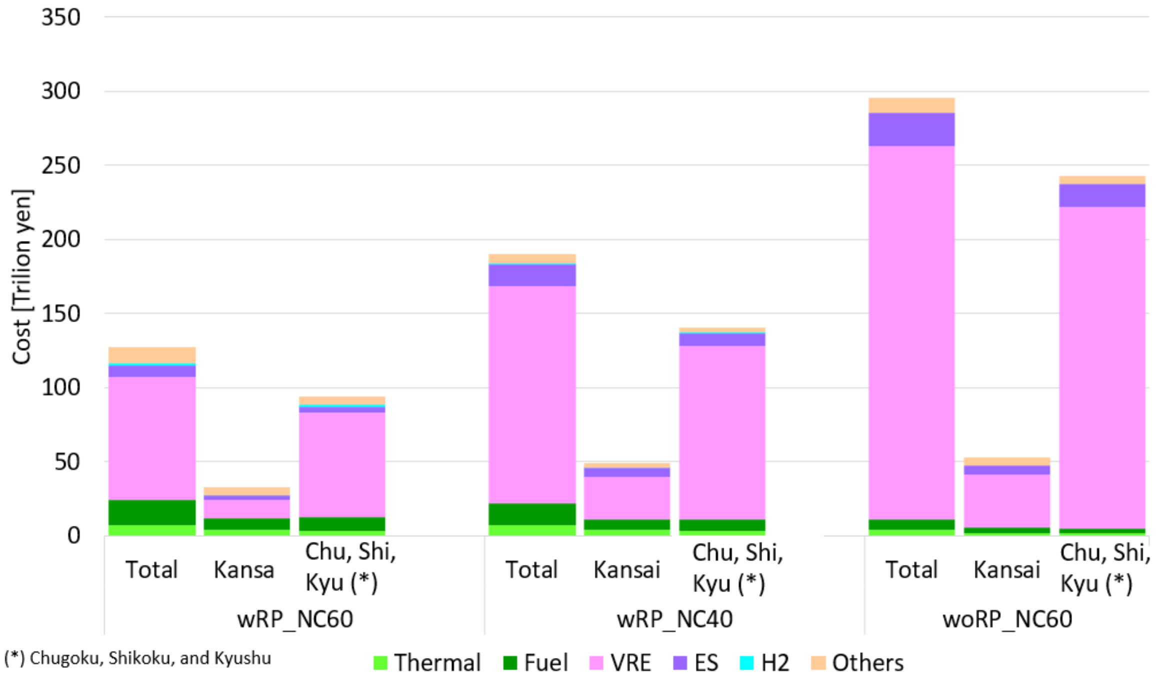
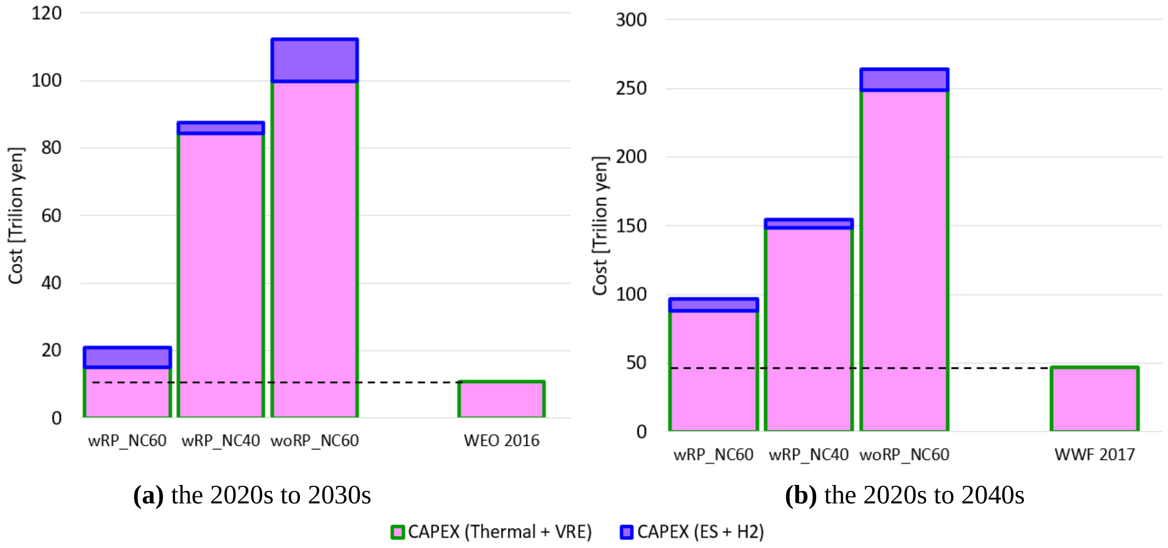


Figure 2.13. Total accumulated costs from the 2020s to 2040s (2020-2049) in each case



(a) the 2020s to 2030s

(b) the 2020s to 2040s

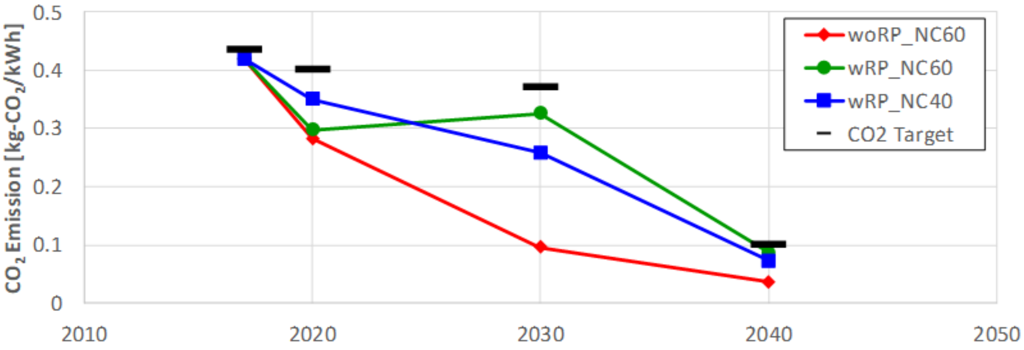
Figure 2.14. Total accumulated costs (CAPEX) compared to other investigations: **(a)** from the 2020s to 2030s (2020- 2039), and **(b)** from the 2020s to 2040s (2020-2049)

2.3.3 CO_2 Emissions

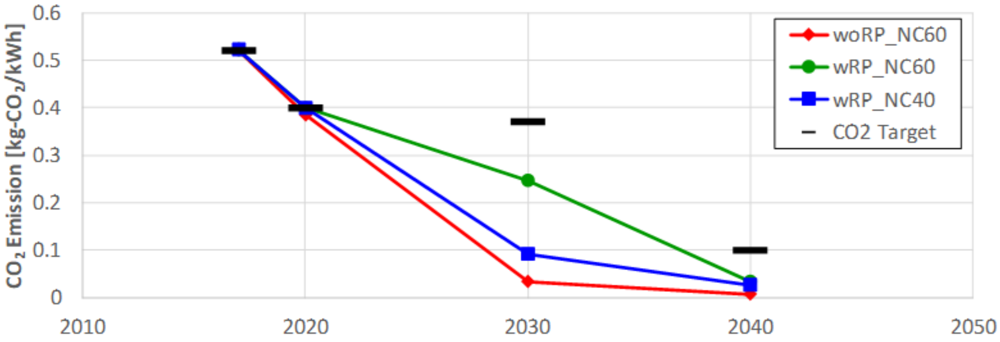
Figure 2.15 shows the CO_2 emission factors for each decade and case, and the restriction of the CO_2 emission factors for each decade.

In 2020, since the Kansai region had fewer coal-fired power plants and more natural gas-fired power plants, the natural gas-fired power plants were mainly used to satisfy the supply-demand balance due to the lower CO_2 emissions from fuel. As a result, the CO_2 emission factor in this region was less than the limitation of the decade. In contrast, the power supply configuration was determined by the need to meet the CO_2 emission factors in the Chugoku, Shikoku, and Kyushu region, which had less natural gas-fired capacity.

After 2030, as described in Section 2.3.1, VRE introduction proceeded in all regions other than in wRP_NC60 in the Kansai region, and the CO_2 emission factors were less than the limitation. This means that the amount of VRE introduction of these cases was determined to satisfy the supply and demand balance due to the insufficient thermal and nuclear power plant capacity, not to meet the CO_2 limitations. The deviations from the CO_2 emission limits were larger in order of woRP_NC60, wRP_NC40 and wRP_NC60 in both regions. These results suggested that the replacement of existing thermal plants to GTCC helped the introduction of VRE efficiently.



(a)



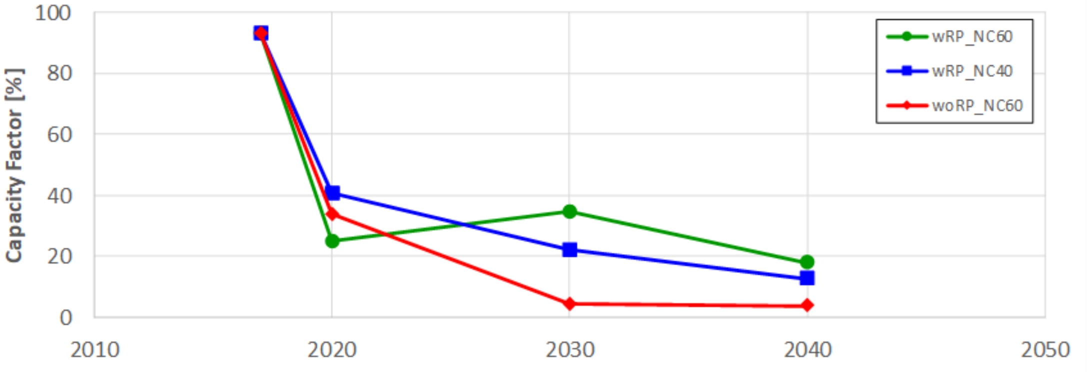
(b)

Figure 2.15. CO_2 emissions in each case: (a) Kansai region and (b) Chugoku, Shikoku, and Kyushu region.

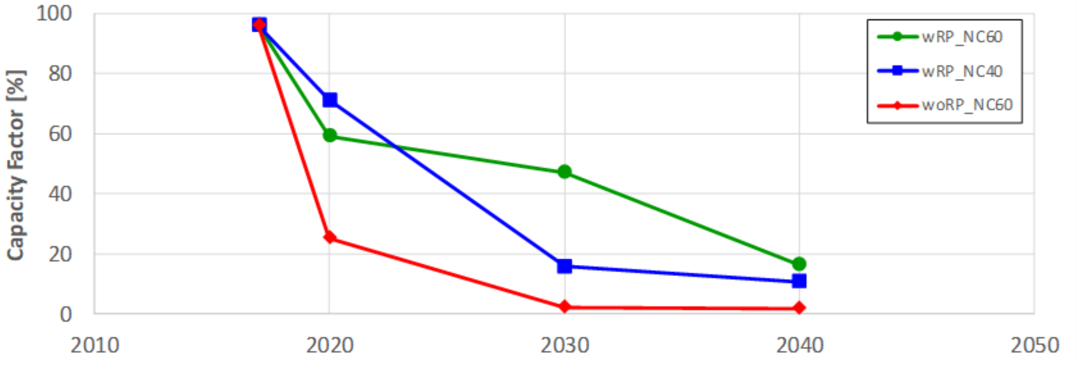
2.3.4 Capacity Factors

Figure 2.16 shows the annual capacity factor of the GTCC for each decade and case. The more the introduction of VRE increased, the lower the capacity factor of the GTCC was in each and region. The capacity factor became less than 20% in all cases by 2040.

On the other hand, **Figure 2.17** shows the capacity factor of the GTCC for each month in 2040 in the case of wRP_NC60. As mentioned above, the capacity factor was less than 20% in all cases as an annual average, but the capacity factor increased in summer and winter when supply and demand were severe. This trend was observed in all cases and was also true in the Chugoku, Shikoku, and Kyushu region, where the GTCC capacity was less than in the Kansai region. In other words, even if the annual capacity factor of GTCC became smaller on the way to the large-scale VRE introduction, the replacement to GTCC could contribute to balance the supply and demand in the highest load seasons and keep the total cost lower.



(a)



(b)

Figure 2.16. Capacity factor of GTCC in each case: **(a)** Kansai region and **(b)** Chugoku, Shikoku, and Kyushu region.

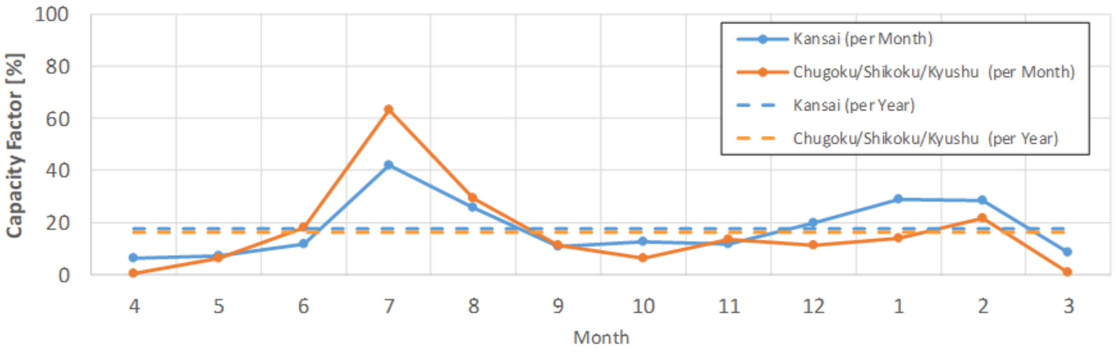


Figure 2.17 Capacity factor of the GTCC facilities for each month in 2040 in case of wRP_NC60

2.3.5 Evaluation of Reserve Ratio

The reserve ratio was not included in the restrictions for the minimum cost calculations in this study in order to clearly show the impact of the replacement and scrapping of existing power generation facilities. However, since securing power capacity (kW) is crucial when RE is to be introduced in large quantities, the reserve ratio was evaluated in this section. (See Appendix A.1.4 for a definition of the reserve ratio.)

Figure 2.18 shows the reserve ratio in August 2040, when a large amount of RE was deployed, and the supply and demand were severe. Although there are various methods for evaluation of the capacity value, such as the K90 method and the Loss of Load Probability (LOLP) method[1] [114], the L5 method was applied in this section for evaluation of the value of PV and wind power capacity using the L5 method, which was one of the common methods for the reserve ratio evaluation; the capacity value is defined by the average of five-day data from the lowest power generation day at the same hour in each month.

As shown in **Figure 2.18 (a)**, the Kansai region, which had a large number of retiring thermal power plants to be replaced, was able to maintain the reserve margin in the case of wRP_NC60 and wRP_NC40. On the other hand, in the case of woRP_NC60, the reserve ratio was always negative. Therefore, it was necessary to store approximately 40% electricity of the maximum demand in batteries or other storage devices against a capacity shortage.

Besides, as shown in **Figure 2.18 (b)**, in the Chugoku, Shikoku, and Kyushu region, where few retiring thermal power plants were replaced, the reserve ratio was negative in all cases. However, the shortfall in the reserve ratio was relatively small if the retiring thermal power plants were replaced by GTCC (wRP_NC60 and wRP_NC40).

That is, it was a preferable scenario to replace retiring thermal power plants with GTCC to support a large amount of RE introduction. Alternatively, considering the fact that there was an area where the reserve ratio was negative in all cases such as the Chugoku, Shikoku, and Kyushu region, another option for the large-scale installation of RE would be to prepare for a capacity shortage by interconnecting power from regions that have reserve margins.

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[1] K90: the capacity factor of a facility over 90% of a year, when the annual capacity factor is arranged in descending order.
LOLP: the number of days in a year when the total supply capacity including reserve capacity is less than the maximum demand [114].

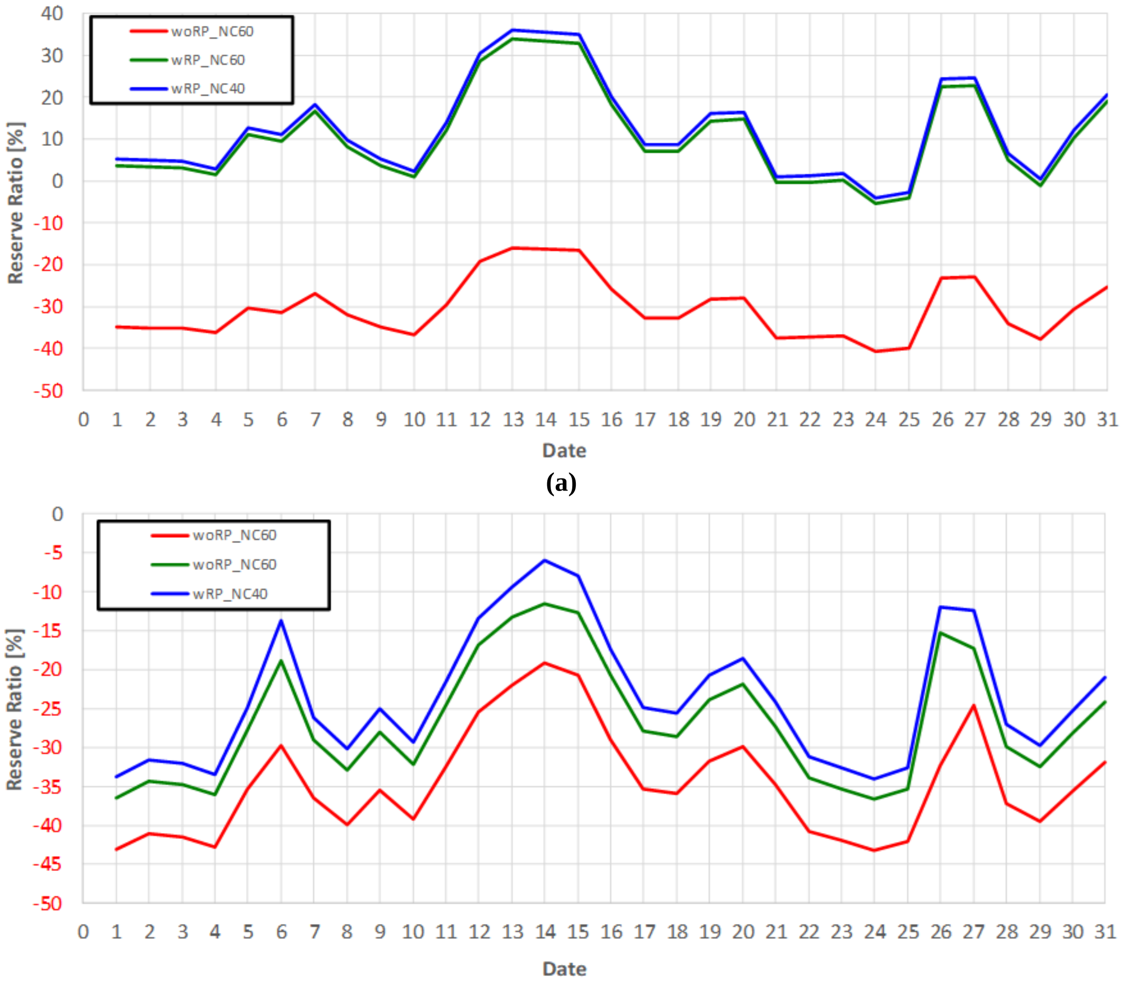


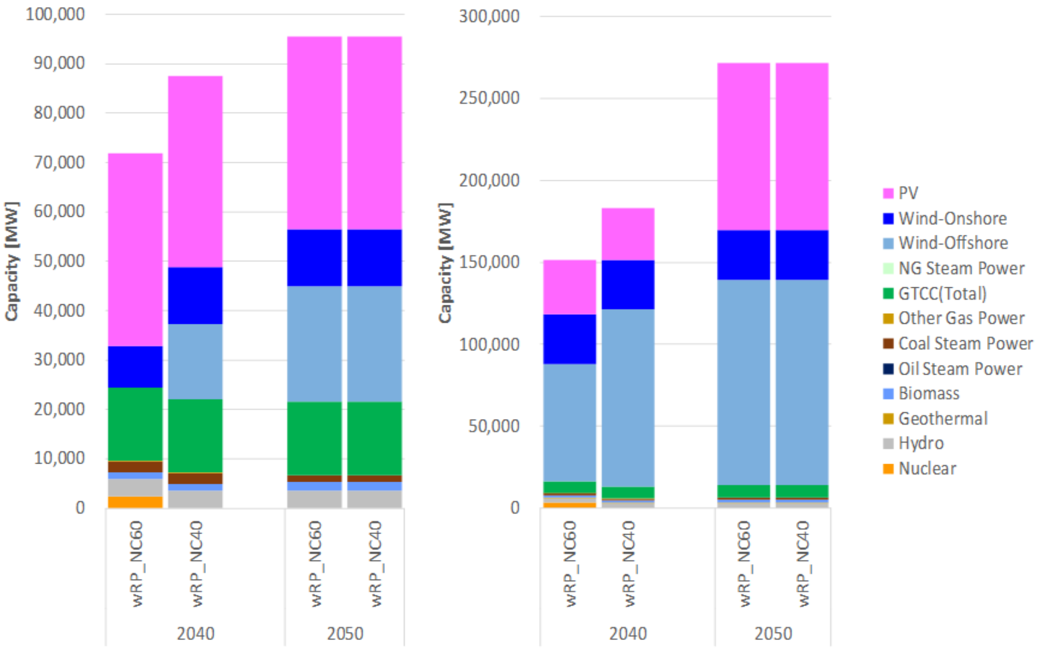
Figure 2.18. Reserve ratio in August, 2040 evaluated by the L5 method

2.3.6 Results of the 2050s

Figures 2.19, 2.20, and **2.21** show the optimal capacities for power generation, energy storage, and hydrogen production in 2040 and 2050, respectively. The CO_2 emissions were zero in 2050 as one of the restrictions. The Chugoku, Shikoku, and Kyushu region could meet the electricity supply and demand from RE sources within the region.

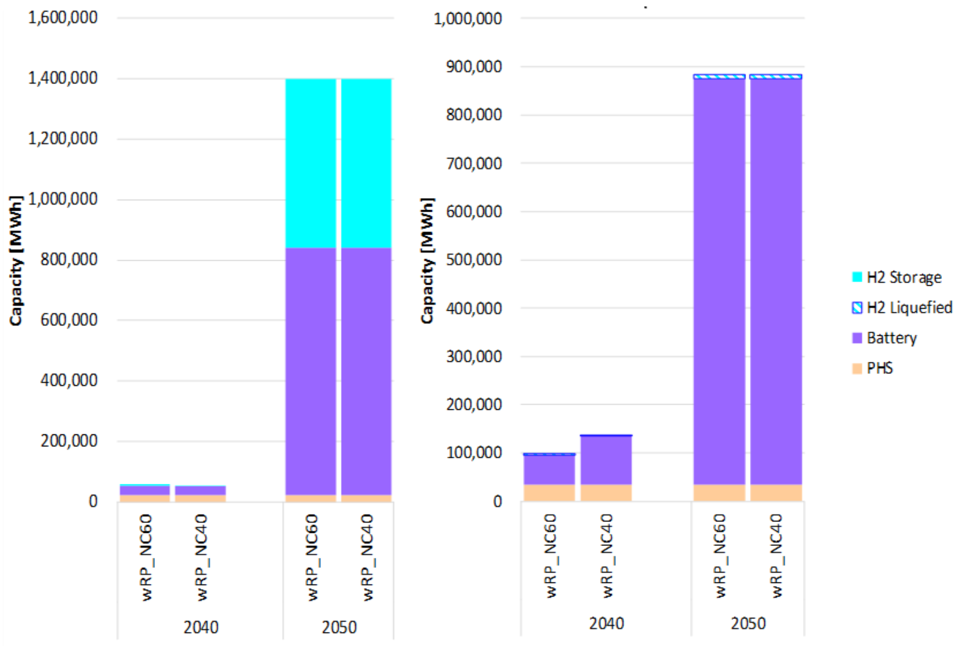
On the other hand, the Kansai region could not fully supply the necessary electricity to satisfy the demand from RE sources inside the region even though the introduced RE hit the maximum potential capacity. In the case of wRP_NC60 and wRR_NC40, in which the optimal energy mix will be the same due to no nuclear capacity in both cases, it was found that the Kansai region could meet the electricity supply and demand by hydrogen fired GTCC with hydrogen transferred from the Chugoku, Shikoku, and Kyushu region. However, in the case of woRP_NC60, there were no solutions that satisfied the supply-demand balance, due to a lack of supply capacity.

Figure 2.21 shows that hydrogen production in the Chugoku, Shikoku, and Kyushu region increased from approx. 5-7 GW in 2040 to 16 GW in 2050, while hydrogen storage capacity in the Kansai region increased substantially from about 3 GWh in 2040 to about 550 GWh in 2050, as shown in **Figure 2.20**. This indicates that in the Kansai region, where the introduction potential of RE was smaller, hydrogen was stockpiled in advance to balance the supply and demand with hydrogen-fired GTCCs when the supply and demand situation was severe. That is, CO_2 reduction and the necessary reserve ratio would be achievable at the same time by replacing retiring thermal power plants with hydrogen fired GTCC and long-term storage of hydrogen with surplus electricity.



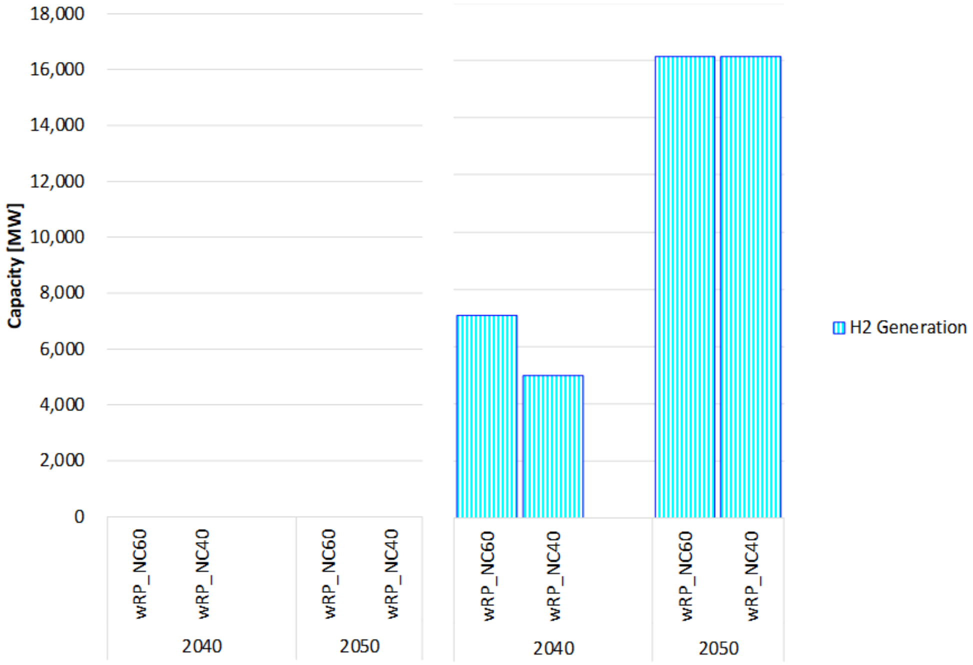
(a) **(b)**

Figure 2.19. Optimal capacity of power generation in the 2040s and 2050s: **(a)** Kansai region and **(b)** Chugoku, Shikoku, and Kyushu region.



(a) **(b)**

Figure 2.20. Optimal capacity of energy storage in the 2040s and 2050s: **(a)** Kansai region and **(b)** Chugoku, Shikoku, and Kyushu region.



(a) **(b)**

Figure 2.21. Optimal capacity of hydrogen generation in the 2040s and 2050s: **(a)** Kansai region and **(b)** Chugoku, Shikoku, and Kyushu region.

2.4 Conclusions

This study focused on the chronological replacement and abolishment strategies of existing power generation facilities in the 2020s, 2030s, 2040 and 2050s, and analyzed the impact of these strategies on the power supply mix and energy storage. As a result, it was clear that the large-scale introduction of VRE with the chronological replacement of retiring thermal power plants would contribute to reducing the total cost during the energy transition, as well as the amount of surplus electricity of RE, under the conditions defined in this study. The following conclusions are drawn for each decade.

In the 2020s, in the scenario of replacing retiring thermal power plants, the increase in VRE will be insignificant, while the introduction of secondary batteries will proceed. This is because the batteries are charged during the night when demand is low, and the discharge of batteries supports the thermal power plant's output during the daytime and evening when demand is high while satisfying the CO_2 limitation. On the other hand, when retiring thermal power plants are not to be replaced, onshore wind and storage batteries increase.

In the 2030s, when a CO_2 emission factor of 0.37 kg-CO_2/kWh is set as a target, installation of wind power will proceed in the case where retiring thermal power plants are not replaced, or thermal power plants are replaced but the lifetime of nuclear power plants is not extended. When the total capacity of thermal and nuclear power plants is equivalent, it is revealed that the replacement of retiring thermal power plants to GTCC can promote VRE introduction efficiently compared to the lifetime extension of nuclear power plants.

In the 2040s, when the large-scale introduction of VRE proceeds under the restrictions of existing power plant replacement, it becomes clear that the introduction of VRE has regional characteristics. PV will increase ahead of wind power in the region where natural gas-fired power generation capacity is large, while wind power will increase ahead of PV in the region where natural gas-fired power generation capacity is small. Additionally, in the scenario of replacing retiring power plants, it is shown that hydrogen as energy storage can reduce the total cost and promote VRE introduction; producing hydrogen with the surplus electricity in regions where a large amount of RE is introduced, and transferring the hydrogen to regions where the GTCC capacity is relatively larger for hydrogen-fired power generation.

In the 2050s, when CO_2 emissions from power generation are set to zero, hydrogen-fired power plants will be permanent facilities in the region where electricity supply and demand cannot be met by RE sources alone. Therefore, it is necessary to encourage thermal power plant replacement in the low RE potential region during the energy transition period. On the other hand, in the region where electricity demand can be met solely by RE sources, thermal power generation will be only a transitional option, although the replaced power plants will balance electricity supply and demand and reduce total cost on the way to a 100% RE society.

CHAPTER 3. Behavioral Decision Making by Power Generation Companies regarding Energy Transitions under Uncertainty

3.1 Introduction

This chapter represents the microscopic perspective of the energy transition, considering the consistency with constraints of existing infrastructures and results in Chapter 2. This study attempts to obtain novel information on RE companies' decision-making behavior under uncertainty in the energy market, which is not yielded by the conventional NPV approach.

While the endpoint of a renewable energy system with the elimination of fossil fuels is theoretically clear, during the transition period power generation companies need to make the decision to invest (or not) in large-scale RE considering various uncertainties such as the level and duration of financial support for RE, fuel price trends, electricity demand, and the strategies of competitors. Given such uncertainties, power generation companies will take different strategies based on their management culture, history and interpretation of the information at hand. The elucidation of how uncertainties affect the investment decisions of power generation companies with regards to RE under different government energy and economic policies to encourage the introduction of large-scale RE is important to continuous improvement of policy measures.

As introduced in Section 1.2.2, the net present value (NPV) method is widely applied in decision making regarding company investments [69,70]. Though the NPV method is regarded as one of the most effective measures for the evaluation of the advantages and disadvantages of investments [59], in reality, it is known that companies often do not make investment decisions even if the expected NPV of the investments are positive [71]. In order to explain this variation, previous studies attempted to apply the real options approach to the evaluation of a company's investments, including RE investments [58–62,73–77]. However, as real options are based on the traditional NPV approaches, the problem of previous studies seems to lie in the fact that the decision-makers are supposed to make rational investment decisions as normative decision making.

On the other hand, some previous literature focuses on non-normative and behavioral perspectives of a company's RE investments [63–66,78]. However, these studies were mostly based on the analysis of questionnaire surveys or qualitative analysis, and few studies have attempted to quantify the values of RE investments from both normative and non-normative perspectives, particularly regarding the decision-making process of power generation companies to invest in large-scale RE.

In this study, focusing on the fact that the non-normative perspective influences decisions of RE investment in addition to the normative perspective, this study designs a novel framework. The framework incorporates both the normative and non-normative decision-making perspectives of RE companies to describe the investment behavior observed in reality, which the conventional NPV approach overlooks. Based on the designed framework, a quantitative decision-making model for the RE company was developed. Besides, various uncertainties that the RE company faces were defined: the power variation of VRE, strategies of competitors, and future policies. This study aims to obtain novel information on the decision-making behavior of RE companies under uncertainty in the energy market, which is not yielded by the conventional NPV approach. The Kansai region in Japan was considered as the study area.

3.2 Methodology

3.2.1 Design of the Framework

When decision making of a company is discussed, the company’s management functions can be summarized into three levels [115,116]: the top management (in charge of strategic decisions), the middle management (the operational decisions), and the first-line management (the administrative decisions), although the company is normally composed of multi-level departments and sections. Since this study considers high-level decisions for RE investment, we focus on the top management and middle management as representing the decision-making processes of the RE company. Companies with bottom-up decision-making management, where the top management makes decisions based on reports and/or proposals from the sections in charge are representative of the traditional infrastructure companies in Japan [117–119]. **Figure 3.1** shows the designed framework of the decision of RE companies in this study. The middle management, in charge of investment planning, prepares possible investment options, analyzes outcomes and probabilities, and provides the analysis results such as the expected NPV of each option to the top management. The top management is the decision-maker, who determines options to be invested in based on the analysis results. The novelty of the framework applied here, is characterized by the non-normative perspectives of the decision-maker being incorporated, in addition to the normative approach, assuming two layers of the RE company’s organization.

Non-normative perspectives were categorized into private, personal, and exogenous influences, considering the decision-making process of companies and a literature survey [63–66]. Private influence stems from within the company and includes suggestions from the middle management to the top management, which are usually given in addition to the economic analysis results. The decision of the top management may be influenced by the suggestions from the middle management. Personal influence expresses the personal beliefs and knowledge of the decision-maker such as beliefs regarding RE technologies. For instance, the decision-maker should have objective information on the applied RE technologies; however, the adequacy for investments could depend on personal beliefs regarding the technologies [120]. Exogenous influence comes from outside the company. For example, RE investors usually take into account the investment decisions of their competitors [63,64]. Based on this framework, we developed the following behavioral decision model of the RE company in the energy market.

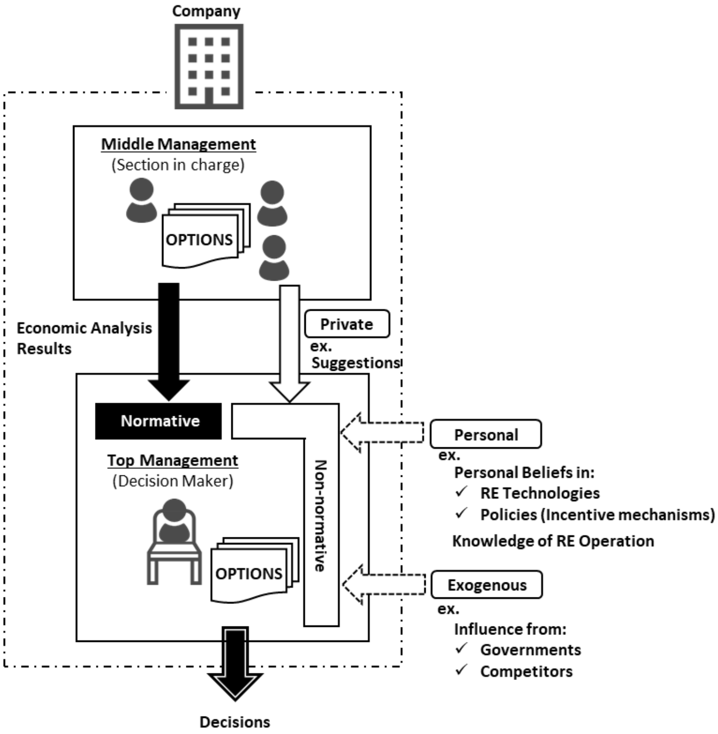


Figure 3.1. Framework of decisions of RE companies based on normative and non-normative perspectives

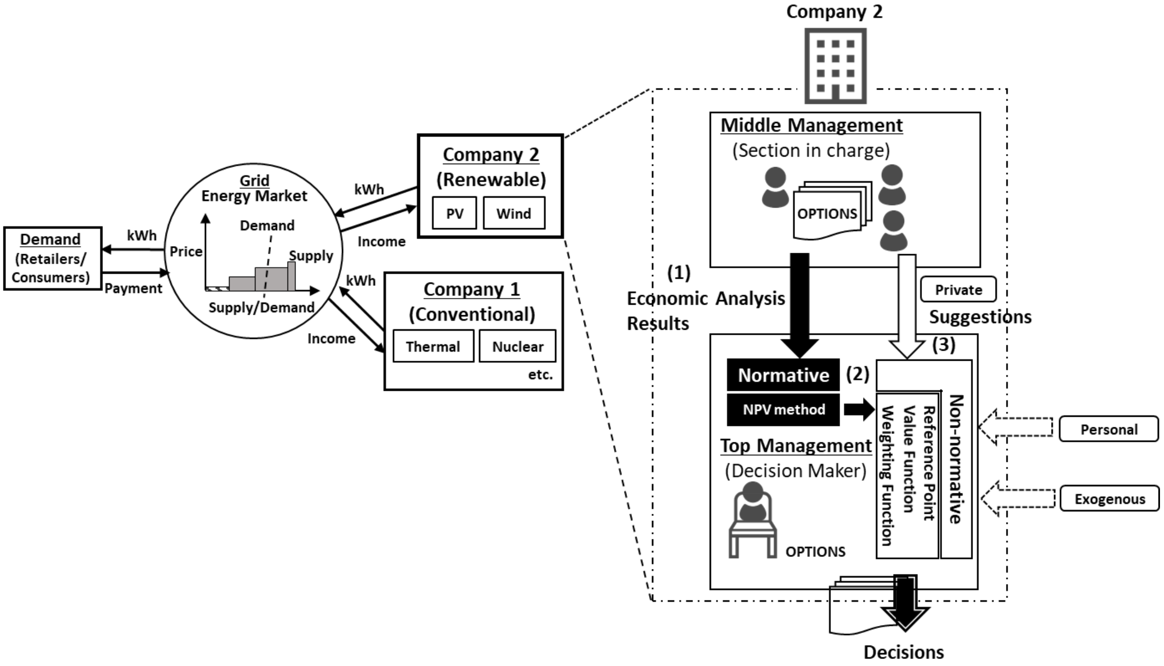
3.2.2 Development of the Behavioral Decision Model in the Energy Market

In this study, two power generation companies were assumed to compete in the energy market. One was a traditional power company that owns large-capacity conventional power generation plants (Company 1) and the other was a renewable power generation company that invests in VRE plants (Company 2), as shown in **Figure 3.2 (a)**.

Focusing on the investment behavior of Company 2, we developed a decision-making model based on the proposed framework. **Figure 3.2 (b)** shows the concept of the developed model that applies concrete methods to quantitatively integrate normative and non-normative perspectives in the framework of **Figure 3.1**. First, the conventional NPV method was applied to the normative perspective of the decisions of the top management since the NPV method is widely used for companies` decisions, as introduced in Sec. 1. That is, the middle management provided the expected NPV and the probabilities of each option to the top management (indicated by (1) in **Figure 3.2 (b)**).

Second, to express the non-normative perspectives of the decision making by the top management in the framework, we referred to approaches of behavioral economics, which were introduced by Kahneman and Tversky [46,47]. They classified an individual's decision-making process into two phases: the editing phase and evaluation phase. In the editing phase, outcomes and stated probabilities of the decision maker's options are analyzed and reformulated. They claimed that a decision-maker converted the outcomes (NPV in this study) of each option to gains and losses relative to a "reference point" (RFP), which can be affected and shifted by the expectations of the decision-maker [46,47]. The idea of an RFP makes their approach unique in that the basis of decisions changes depending on how people feel (the RFP applied to this study is defined in Sec. 3.2.4); in contrast, since conventional economics, including expected utility theory, assume that people make decisions rationally, so the basis for decisions do not change. In the evaluation phase, the converted gains/losses and probabilities of each option are evaluated with a "Value Function" and "Weighting Function", and the value of each option is determined in the decision-maker's mind (indicated by (2) in **Figure 3.2 (b)**). The value function expresses the decision-maker`s tendency to be risk-averse in the case of a risky option leading to gains, and risk-seeking in the case of a risky option leading to losses. They also observed a trend that individuals tended to overestimate small probabilities and underestimate large probabilities, and a weighting function was introduced to express this trend [46,47].

The RFP of the decision-maker can be expected to be affected by private, personal, and exogenous influences, which are incorporated in the designed framework in this study (indicated by (3) in **Figure 3.2 (b)**). The decision given by the value and weighting functions may vary if the RFP is shifted despite the similarity of the incomes and probabilities of each option. We expected these ideas to fit well into the non-normative perspectives in the designed framework (see Appendix A for further details on reference point and value and weighting functions).



(a) (b)

Figure 3.2. Overview of the developed model based on the designed framework: **(a)** Companies in the energy market and **(b)** Application of the framework to the decision-making process Company 2.

Considering the conventional NPV method for the normative perspective and the behavioral approach for the non-normative perspective as stated above, a decision-making model was developed to examine the decisions of Company 2 regarding preferred investments under various uncertainties. The model is summarized in **Figure 3.3**, which further elaborates on the details of **Figure 3.2** and consists of the following five steps:

STEP I: Information Gathering

Necessary information is defined as simulation input in this step. Private information (STEP 1-a) is the known data determined by Company 2: existing VRE capacity owned by Company 2, strategies for newly invested VRE capacity, the initial cost of VRE, operation and maintenance cost, and discount ratio. Exogenous information (STEP 1-b) is uncertain for Company 2 and some information is obtained from a probability distribution such as fuel price for fossil fuel-fired power plants owned by Company 1, electricity demand in the energy market, and VRE outputs affected by ambient conditions. The remaining factors are obtained by scenarios such as future policies and strategies of Company 1. The Kansai region in Japan was considered as the study area; details of input data are described in Sec. 3.2.3.

STEP II: Calculation with Uncertainties in the Energy Market

The middle management of Company 2 incorporate the gathered information into the energy market model to calculate NPV and other parameters for the evaluation of investment with respect to each strategy. Though there have been several previous studies on the energy market of RE [121,122], this study assumes that the energy market is competitive and not dominated by Company 1. The hourly spot price of electricity (Yen per kWh) is decided based on the supply curve generated by the energy supply capability of both companies and the demand obtained from the input of STEP I. Furthermore, the spot price is applied to all supply capacities of technology that are below the demand. Both companies simultaneously provide power generation cost (yen/kWh) and energy supply capacity (kW) of each technology to the market model hourly, and the merit order of power generation creates the supply curve. As the energy market is competitive, the marginal cost of power generation, which consists of fuel cost for power generation (only for thermal power) and O&M cost, is expected to encompass the cost of generating power. Both companies attempt to recover initial investment using the income obtained from the energy market. However, if the cost of generating power of all technologies is the marginal cost, it is known that the capital investment of power generating facilities can be possibly never recovered by the income obtained from the energy market, which is called the so-called "missing money problem" [123]. Therefore, the power generation cost of the replaced thermal power plants is assumed to include the initial investment only when Company 1 invests in the replacement of retiring thermal power plants to avoid the "missing money problem" in the market.

As some of the inputs are obtained through probability distributions, iterative calculations using the Monte Carlo method were adopted. The number of trials for each calculation case was set as 1,000 considering calculation accuracy and time; each calculation case provided 1,000 sets of the output of each company including NPV and CO2 emissions. The given probability distribution, expected value, standard deviation, and conditional value at risk (CVaR) of each output set were then obtained from the model (refer to Appendix B.2 for the definition of NPV and other outputs in this study).

STEP III: Provision of Calculation Results of Each Strategy

Calculation results in STEP II, such as the expected value of NPV, are provided to the top management. As mentioned in Section 3.2.1, when the middle management reports to the top management, in reality, the middle management is supposed to provide suggestions on strategies, and these suggestions could affect the decisions made by the top management. As mentioned earlier, the influence of suggestions is considered as the reference point in this study, and the RFP of this study is obtained based on the calculation results in STEP II and the use of one of the inputs in STEP IV in the model. The RFPs in this study are defined in Section 3.2.4. As we defined the private, personal, and exogenous factors as influencers of the non-normative perspectives in the framework in Section 3.2.1, the belief in RE investments of the top management, the government's announcement of new RE policies, or other factors may influence the top management's decision. However, we only consider private suggestions as influences in the model for simplicity.

STEP IV & V: Calculation of Values and Provision of Output for Each Strategy

If the top management is ideally rational, they should select a strategy with the highest expected NPV. However, in reality, when the top management makes decisions, the decisions ordinarily include their objective and subjective perspectives. To reflect aspects in the decision-making process, the value function relative to the RFP and the weighting function of the top management are incorporated in the model. **Figure 3.4** shows the calculation process of the RE investment value. (1) The NPV calculation and corresponding probability are provided from STEP III. (2) The gain / loss, which the top management "feels", is given by subtracting RFP from NPV (the definition of RFP in this study is in Sec. 3.2.4.) (3) The gain/ loss is converted to a value by the value function. (4) The given probability is then transformed to a subjective probability by the weighting function. (5) The value is multiplied by the subjective probability and the "Value" which the top management determine is obtained. "Value" with a capital V means the outcome calculated by the Value and weighting functions unless otherwise noted. (6) Summation of the Value of each calculation brings the expected Value for the decision. The functions are defined in Appendix B.1.

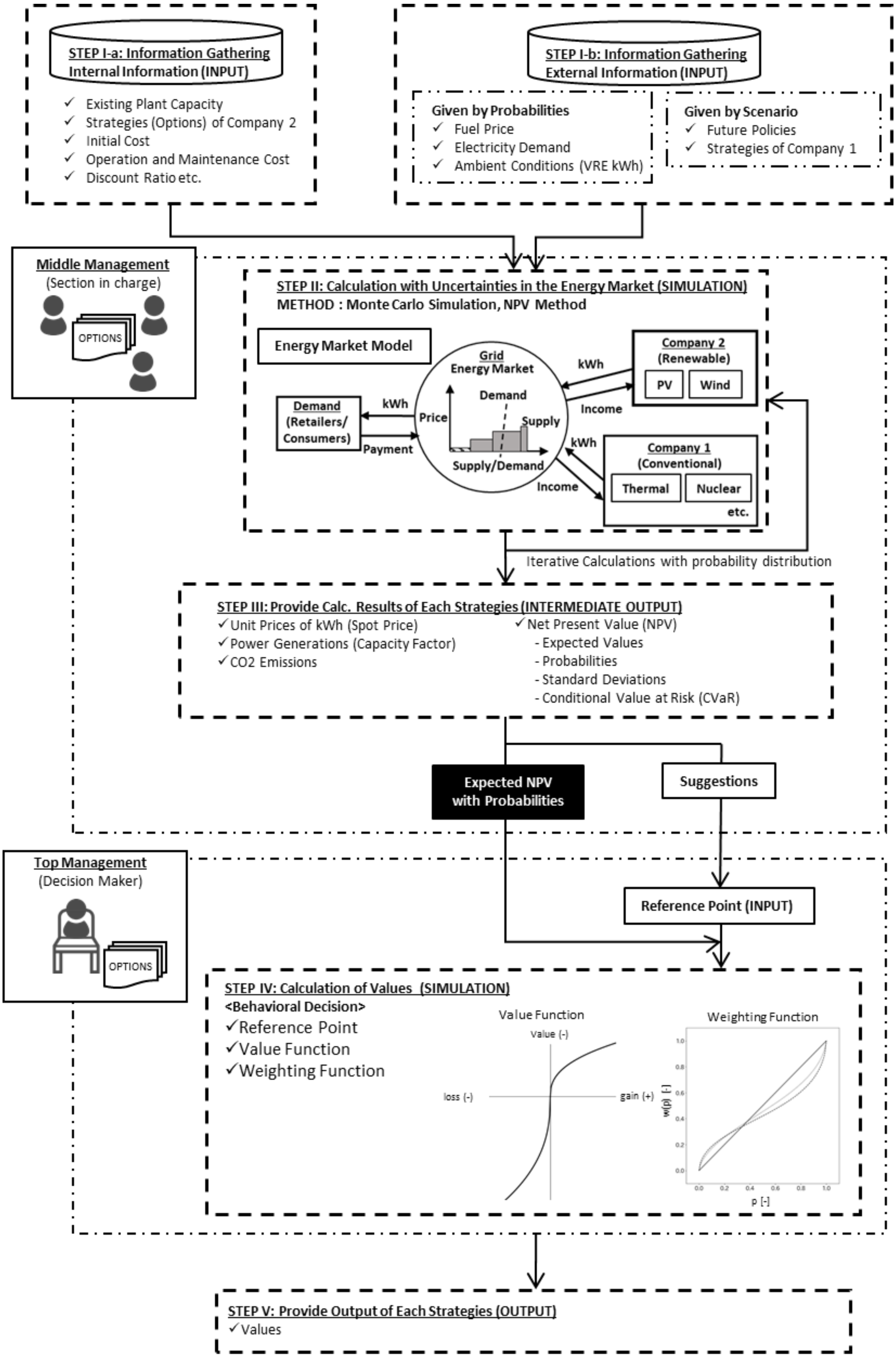


Figure 3.3. Calculation steps of the developed behavioral decision model of Company 2

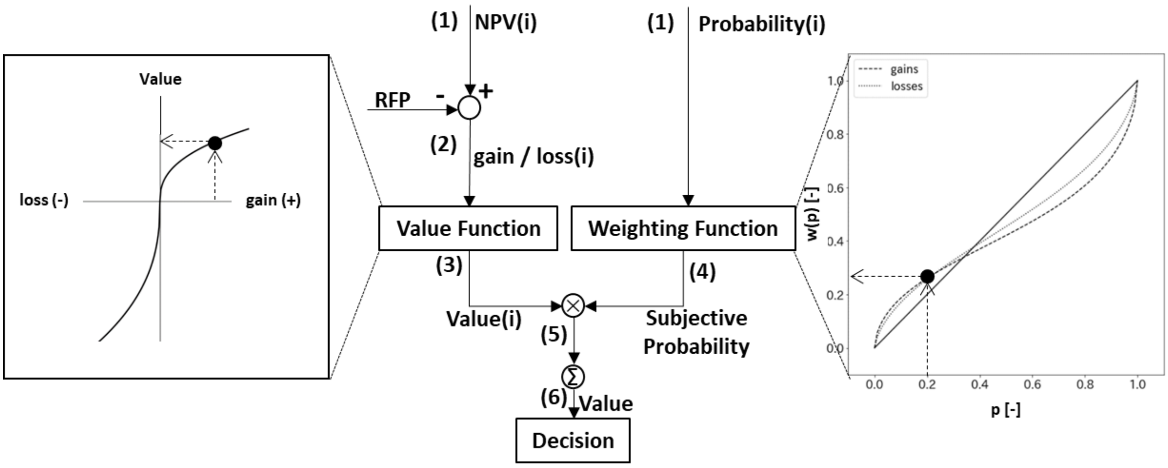


Figure 3.4. Calculation process of the VRE investment value in STEP IV: (1) – (6) are corresponding to the numbers in the description of STEP VI. The black dots in the graphs are examples.

3.2.3 Application to Kansai Region, Japan

3.2.3.1 Overview of Electric Utility System in Japan

The power grid in Japan is characterized by a longitudinal transmission system (**Figure 3.5**), without international connections, and split into ten regions. Each region has one large conventional electric company, and the transmission system of each area is independent because power interconnection is limited to the neighboring area. Here, the Kansai region, which is one of the ten regions and the second-largest economic area in Japan, was selected, and the developed model is applied to the region in this study. Kansai region has KEPCO as the large conventional electric company, and KEPCO is regarded as Company 1 of the model. Though there are several independent power producers (IPPs) other than KEPCO in the area, these IPPs are considered a single company that is Company 2 for simplicity in the model.

An overview of the current and expected future electricity supply/demand system is shown in **Table 3.1**. The deregulation of the electrical utility system in Japan is still underway; most electricity trade is bilaterally conducted over the counter between electric companies and consumers, power generation companies provide electricity supply, a Feed-in tariff is given to newly installed RE, and changes in fuel price can be passed on through the retail electricity price as of 2020. However, considering the timeframe of the energy transition discussed in this study, we incorporated the future expectation into the spot price market model; electricity is mainly traded in the spot price market, transmission operators are responsible for the supply of electricity, feed-in-premium is applied as financial support for RE, and fuel price uncertainty risk is covered by the income of the spot price market.

With regards to the timeframe of this study, Company 2 was expected to decide on investment in VRE in 2025, considering income from the spot price market for the coming 20 years in various scenarios. Properties of applied technologies are listed in Appendix B.3.

Table 3.1. Current and future electric utility system in Japan

	Currently (As of 2020)	Future expectation according to this study
Electricity trade	Bilaterally over the counter	Energy market
Electricity supply responsibility	Power generation companies	Transmission operators
Financial support for renewable	Feed-in tariff	Feed-in premium
Fuel price uncertainty risk	Passed on retail electricity price	Covered by the income of the energy market

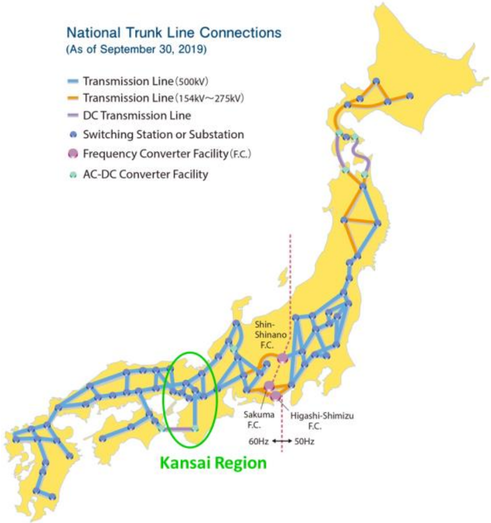


Figure 3.5. National power grid in Japan and Kansai region (Based on [5])

3.2.3.2 Private Information of Company 2 (STEP I-a)

(i) Existing VRE Capacity

Existing VRE capacities owned by Company 2 were set, as shown in **Table 3.2**, considering installed capacity in the Kansai region as of 2019 [124]. The capacities decrease during 2035–2044 compared to the period ranging from 2025–2034 because the VRE lifetime ends. That is, half the existing VRE were assumed to be retired due to their lifetime. The initial cost of these existing VRE was considered to have been recovered, and feed-in-premium (FIP) was not given to the power generation of the equipment.

Table 3.2. Existing VRE capacity of Company 2

	Period	
	2025–2034	2035–2044
PV	4,200 MW	2,100 MW
Wind (onshore)	150 MW	75 MW

(ii) Strategies of Company 2

Company 2 makes decisions to invest in PV and/or wind (onshore). Though there are several types of RE other than PV and wind (onshore) such as biomass, geothermal, wind (off-shore), etc., we focused on PV and/or wind (onshore) in this study. The strategies of Company 2 are summarized in **Table 3.3**. Each strategy has five different options (0MW –7000MW) of capacity to be invested, and 0MW means that Company 2 keeps its existing capacity and does not make any investments in new VRE equipment. As a result of the simulation, the top management was expected to select an option that earns the highest Value. "OE" in the strategy names stands for "option to expand." Strategy names with "OE" mean that Company 2 has the option to expand the capacity of VRE; Company 2 decides to invest in half the capacity of each option in 2025 and decides to develop the remaining half in 2030 only if one-third of the first half capacity's initial cost was expected to be recovered within five years (2025–2029) as a result of the simulation. Other than these cases, Company 2 decides to invest in VRE in 2025.

Table 3.3. Strategies of Company 2 for investment in VRE

Strategy	VRE	Capacity to be invested [MW]								
		0MW	1000MW		3000MW		5000MW		7000MW	
PV_ONLY	PV	0	1,000		3,000		5,000		7,000	
	Wind	0	0		0		0		0	
WIND_ONLY	PV	0	0		0		0		0	
	Wind	0	1,000		3,000		5,000		7,000	
MIX1 (PV:Wind = 1:1)	PV	0	500		1,500		2,500		3,500	
	Wind	0	500		1,500		2,500		3,500	
MIX2 (PV:Wind = 7:3)	PV	0	700		2,000		3,500		4,500	
	Wind	0	300		1,000		1,500		2,500	
MIX3 (PV:Wind = 3:7)	PV	0	300		1,000		1,500		2,500	
	Wind	0	700		2,000		3,500		4,500	
Option to Expand (OE)			***2025***	***2030***	***2025***	***2030***	***2025***	***2030***	***2025***	***2030***
PV_OE	PV	0	500	500	1,500	1,500	2,500	2,500	3,500	3,500
	Wind	0	0	0	0	0	0	0	0	0
WIND_OE	PV	0	0	0	0	0	0	0	0	0
	Wind	0	500	500	1,500	1,500	2,500	2,500	3,500	3,500

3.2.3.3 Exogenous Information: Scenario Development (STEP I-b)

(i) Strategies of Company 1 Regarding Existing Power Plant Replacement

Company 1 owns a large-capacity of thermal power and nuclear power plants, and some of them are supposed to be retired chronologically, which is consistent with the lifetime of the existing facility in the Kansai region. Therefore, Company 1 needs to make decisions on the retiring power plants: replace, scrap, or prolong them. The following strategies are given in this study, which are consistent with strategies given in Section 2.2.3 of Chapter 2.

Strategy T-1: Replacement of Retiring Thermal Power Plants to GTCC

Company 1 replaces retiring thermal power plants with the latest GTCC plants in each period if they have passed 40 years since the start of commercial operation.

Strategy T-2: Scrapping of Retiring Thermal Power Plant

Company 1 scraps retiring thermal power plants in each period if they have passed 40 years since the start of commercial operation.

Strategy N-1: Life Extension of Retiring Nuclear Power Plants

Company 1 gets the approval for extending the lifetime of retiring nuclear power plants from 40 to 60 years by the Japanese Government.

Strategy N-2: Scrapping of Retiring Nuclear Power Plants

Company 1 scraps retiring nuclear power plants in each period if they have passed 40 years since the start of commercial operation.

Three scenarios are developed from combinations of the strategies above, as shown in **Table 3.4**. However, a scenario composed of Strategy T-2 and N-2 (NO replacement of thermal power nor NO lifetime extension of nuclear power) is excluded because the power supply capacity to the energy market is insufficient. Corresponding equipment capacities of each scenario are shown in **Figure. 3.6**, and are estimated based on KEPCO's existing power plants [100,106,125]. These conditions are the same as those in Section 2.2.5 of Chapter 2 other than limiting to Kansai as the region and adjusting the timeframe in this study. "wRP_NC60" is used as the base scenario.

Table 3.4. Strategies of Company 1

Scenario name	Thermal power	Nuclear power
wRP_NC60 (Base)	T-1	N-1
wRP_NC40	T-1	N-2
woRP_NC60	T-2	N-1

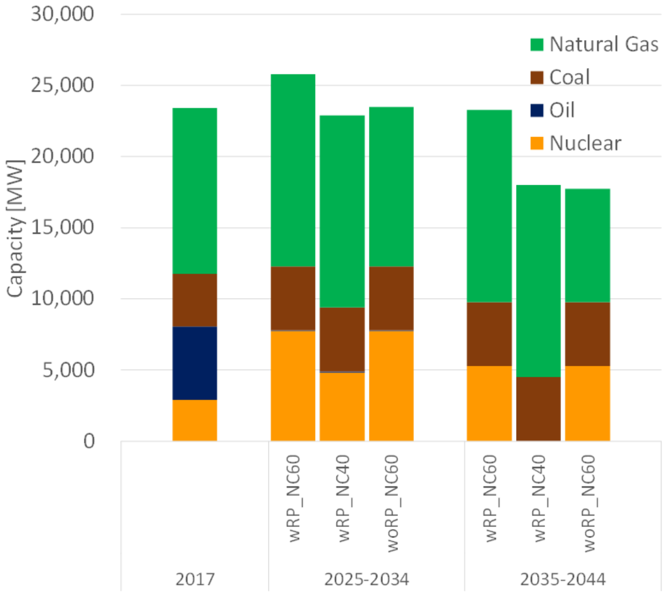


Figure 3.6. National power grid in Japan and Kansai region

(ii) Future Policies

Feed-in Premium (FIP)

There are several types of financial support for RE examined by governments around the world (**Figure 3.7**), and "Fixed Feed-in Premium," where a fixed premium was given on top of the spot price of the energy market, was selected as financial support in this study. Because the FIP follows the spot price, it is expected to be suitable for the investigation of the impact of VRE introduction to the spot price market. In this study, different prices of FIP for PV and wind were set as scenarios as shown in **Table 3.5**.

Table 3.5. Scenarios of financial supports for VRE

Scenario name	FIP [yen/kWh]	
	PV	Wind (offshore)
FIP-Low	10	5
FIP-Mid	12	8
FIP-High	15	10

Figure 3.7. Examples of FIP

3.2.3.4 Exogenous Information: Probability Distribution (STEP I-b)

(i) Fuel Price

Fuel prices of natural gas, coal, and oil in each year were assumed to stem from the triangular distribution in **Table 3.6** into the model to express the future uncertainty of the fuel price. Data from the World Energy Outlook of IEA were referenced [108].

Table 3.6. Fuel gas price

Fuel	Fuel price		
	Low	Mode	High
Natural gas [\$/Mbtu]	8.8	9.7	11.0
Coal [\$/ton]	65	86	94
Oil [\$/Barrel]	62	88	111

\$1 = ¥ 110

(ii) Electricity Demand

The recorded data of electricity demand of the Kansai region in 2017 was used as input into the spot price market model as a basis. We also estimated the uncertainty of change in demand from 2025 through 2044 (20 years) as ± 10% in this model [108,126]. The probability distribution of the demand was given by a uniform distribution (rectangular distribution).

(iii) Ambient Conditions

Trends of unit output (kWh/unit) of PV and wind (onshore) were estimated using PV and wind output (kWh) recorded data of the Kansai region in 2017 [126]. The trends of unit output were implemented into the spot price market model as a basis. As changes in PV and wind output due to ambient conditions were considerably uncertain for the investment of Company 2, the uniform distribution of ± 15% was considered for changing output according to ambient conditions, based on historical data in the Kansai region.

3.2.4 Study Cases

Study cases are summarized in **Table 3.7** and comprise the strategy of Company 2 and scenarios on the strategy of Company 1, FIP price, and CO2 restrictions. Company 2 has seven strategies defined in Table 4, and Company 1 has three strategies described in **Table 3.4**, respectively. As mentioned in Section 2.2 (STEP III), the creation of RFPs in each case was necessary. **Figure 3.8** shows the concept of RFP selection for the decision making of the top management in this study. The middle management provides the NPVs and probabilities of each investment option to the top management, which correspond to the histogram in **Figure 3.8**. We expect that the top management will decide the capacity of the VRE investment based on the anticipated income of each option compared to that of the option 0MW (defined in **Table 3.3**), where the existing facility owned by the Company 2 earns income and there is no investment in new VRE. Though there are multiple possible RFPs in reality as shown in **Figure 3.8**, two types of RFPs were adopted in this study for simplicity of the model; the expected value of NPV (Ref_EXP) and CVaR of NPV (Ref_CVaR) in case of 0MW. We assume that the top management will evaluate the VRE investment based on the expected value of NPV of 0MW when the middle management emphasizes the "profit" of VRE investments (positively frame) in their suggestion to the top management. On the other hand, the top management will evaluate the VRE investment based on the CVaR of NPV of 0MW when the middle management emphasizes "risk" of the VRE investments (negatively framed). According to the definition of the reference point described in Appendix A, the different reference points bring different gains or losses even if the outcomes (NPV in this study) are the same; gains are smaller, and losses are bigger in the case of ReF_EXP compared to ReF_CVaR, which the decision-maker "feels." For example, in case the expected value of NPV in OP-0MW (Ref_EXP) is 300 Billion yen, the CVaR of NPV in 0MW is -100 Billion yen, and a 1000 MW PV investment brings 400 Billion yen of NPV, the gain that the top management feels at Ref_EXP will be +100 Billion yen (= 400 Billion yen – 300 Billion yen), and +500 Billion yen (= 400 Billion yen –(- 100 Billion yen)) at Ref_CVaR (these values are just examples.) Preparing for the two cases of RFP as shown in **Table 3.8**, the influence of suggestion (RFP) provided by the middle management was observed. Scenarios indicated by yellow highlighted areas with underscores in Table 8 are items for comparison in each case.

Table 3.7. Summary of study cases

Case No.	Strategy of Company 2 (**Table 3.3**)	Combination of scenarios	
		Company 1 (**Table 3.4**)	FIP Price (**Table 3.5**)
1	PV_ONLY	wRP_NC60	FIP-Low FIP-Mid FIP-High
2	WIND_ONLY	wRP_NC60	FIP-Low FIP-Mid FIP-High
3	PV_ONLY	wRP_NC60 wRP_NC40 woRP_NC60	FIP-Low
4	WIND_ONLY	wRP_NC60 wRP_NC40 woRP_NC60	FIP-Low
5	PV_ONLY_ MIX1(PV:Wind = 1:1) MIX2(PV:Wind = 7:3) MIX3(PV:Wind = 3:7) WIND_ONLY_	wRP_NC60	FIP-Low
6	PV_ONLY_ MIX1(PV:Wind = 1:1) MIX2(PV:Wind = 7:3) MIX3(PV:Wind = 3:7) WIND_ONLY_	wRP_NC60	FIP-High
7	PV_ONLY_ PV_OE	wRP_NC60	FIP-Low
8	WIND_ONLY_ WIND_OE	wRP_NC60	FIP-Low
9	PV_ONLY_ PV_OE	wRP_NC60	FIP- High
10	WIND_ONLY_ WIND_OE	wRP_NC60	FIP- High

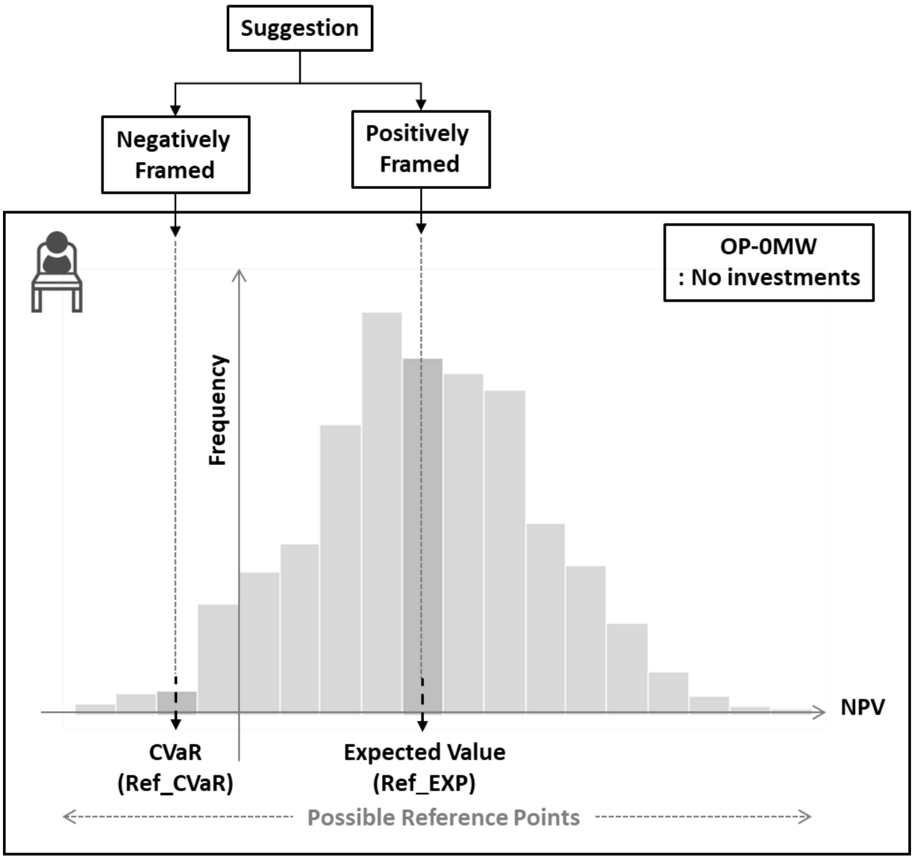


Figure 3.8. Concept of selected reference points for the decision making of the Top management

Table 3.8. Types of reference point

Reference point name	Remark
Ref_EXP	Expected value of NPV in the option of 0MW of each case (Higher RFP)
Ref_CVaR	CVaR NPV in the option of 0MW of each case (Lower RFP)

3.3 Results and discussion

Simulation results of each case are shown in the following subsections to examine the decision making by Company 2. If the top management is ideally rational, they should select a RE capacity with the highest expected NPV. However, the top management would invest in the RE capacity with the highest value from a behavioral decision perspective. Therefore, we evaluated the results focusing on differences in the trend of expected NPV and value in each strategy. Although graphs are shown to illuminate the trend, digital data of calculation results in each case corresponding to the figures are available in Appendix B.4. The cases of each subsection correspond to the case number in **Table 3.7**, and legends of the figures are in line with the scenario names in **Tables 3.3, 3.4, 3.5**, and **3.6**.

3.3.1 Effect of FIP Price (Case 1 & 2)

Figure 3.9 shows the expected NPV reported to the top management by the middle management, the Value given by the NPV in the top management's mind, and the average spot price in the spot price market. There are two alternative Values: Ref_EXP (high RFP) and Ref_CVaR (low RFP) cases as defined in **Table 3.8**. The horizontal axis of each graph is the total VRE capacity which Company 2 decides to invest in. The error bars in the NPV graphs represent the standard deviation of the NPV. The left side of the figure represents the evaluation of the investment in PV, and the right side represents that of wind.

In the scenario with high FIP, investment in 5,000 MW capacity earned the largest expected NPV, and the 7,000 MW investment yielded a relatively lower NPV due to spot price decrease for both PV and wind cases (**Figure 3.9 (a)-PV, (a)-wind**); Company 2 should decide to invest in 5,000 MW of PV or wind, from the standpoint of economic rationality. On the other hand, when the top management interpreted the expected NPV with probabilities through the Value and weighting functions, 3,000 MW for PV and 5,000 MW for wind yielded the highest Value for both Ref_EXP (high RFP) and Ref_CVaR (low RFP). The selected capacity shifted from 5,000 to 3,000 MW for PV (**Figure 3.9 (b)-PV, (c)-PV**), and Company 2 decided to invest in a capacity that was lower than the economic optimum.

In the scenario with low FIP, additional investment in VRE yielded lower expected NPV because the initial cost of VRE could not be recovered by income from the spot price market (**Figure 3.9 (a)-PV, (a)-wind**), and the same trend was given in the Value with Ref_EXP. However, observation of the Value with Ref_CVaR showed that the Value of 1,000 MW remained slightly positive (**Figure 3.9 (c)-PV, (c)-wind**). These results imply that the top management may decide to invest in a small capacity of VRE despite low financial support when the middle management made a suggestion that shifted the RFP of the top management downwards, as represented by Ref_CVaR in this study.

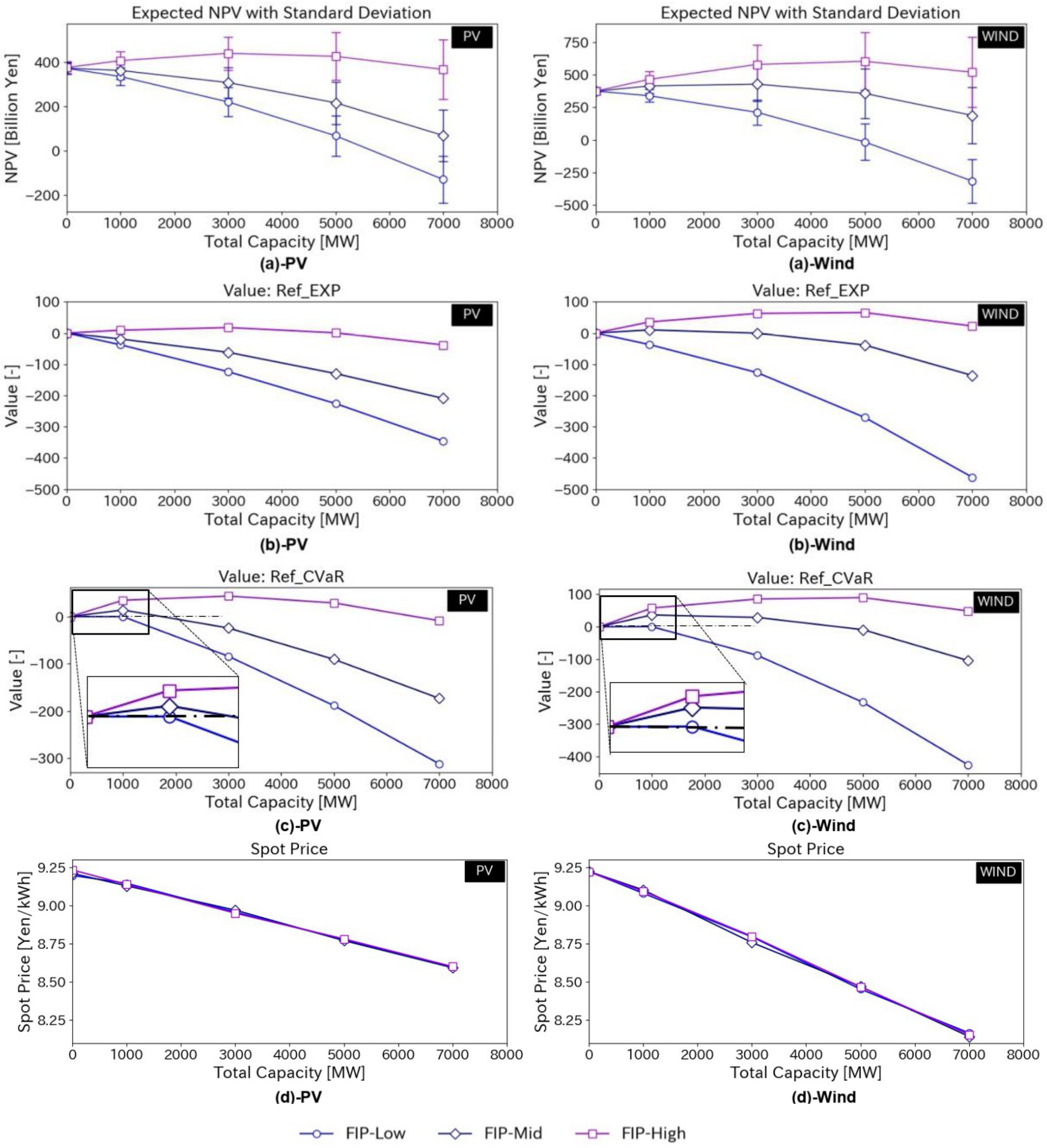


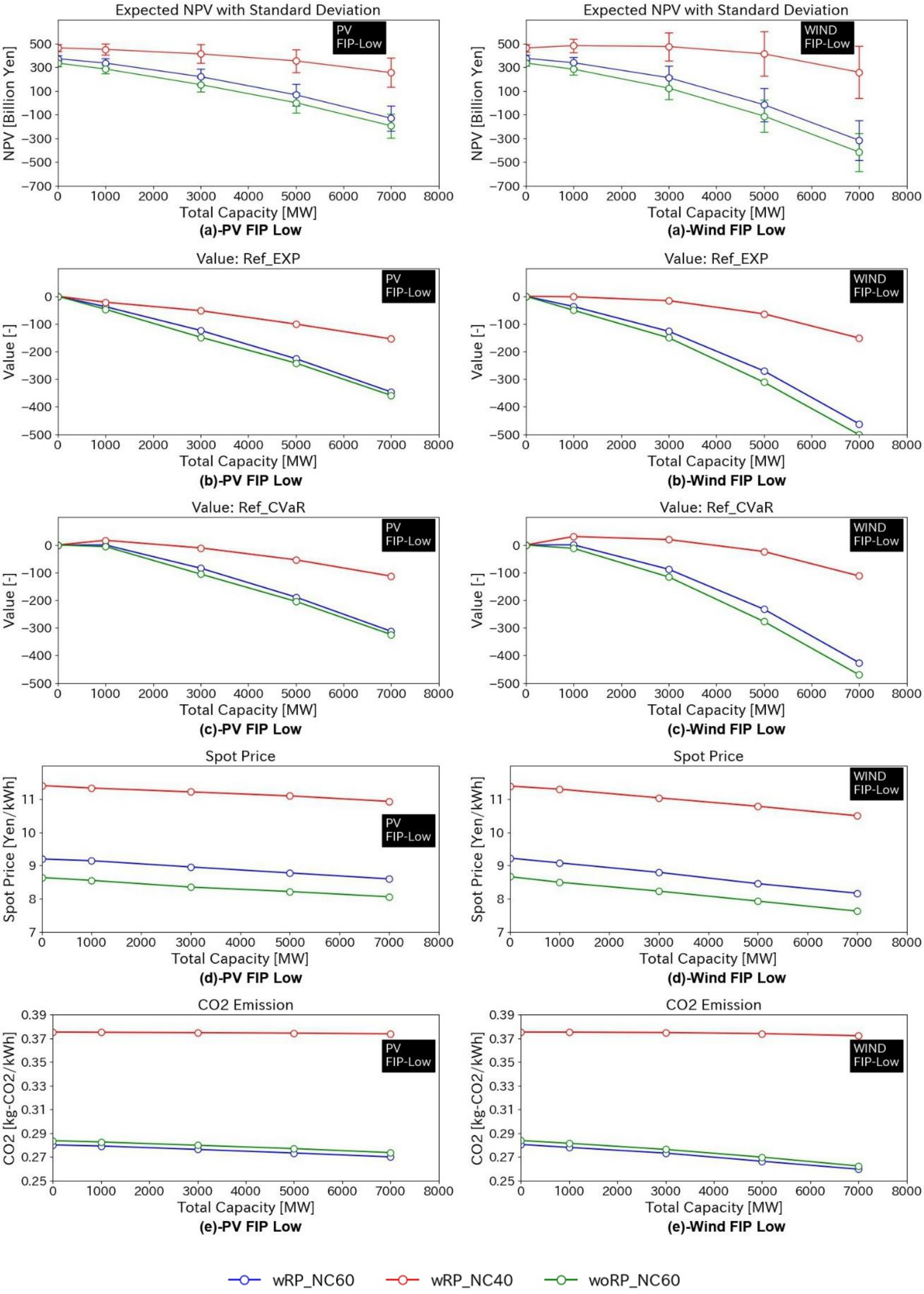
Figure 3.9. Results of different FIP prices (Low, Middle, and High FIP): **(a)** Expected NPV with Standard Deviation, **(b)** Value in case of high RFP, **(c)** Value in case of low RFP and **(d)** Spot price. The horizontal dashed lines show the zero axis in the Value graphs

3.3.2 Effect of Company 1's Strategy (Case 3 & 4)

Figure 3.10 shows the results of different strategies of Company 1 with low FIP. Company 2 acquired the largest expected NPV and Value in the case of wRP_NC40, which was the scenario in which Company 1 replaced retiring existing thermal power plants and scrapped retiring existing nuclear power plants. This is because Company 2 could expect higher spot prices because of the reduced capacity of nuclear power plants allowing for a larger capacity factor of thermal power plants in this scenario. However, it should be noted that the CO2 emissions in this scenario were approximately 0.1 kg-CO2/kWh higher than that in the other two scenarios (**Figure 3.10 (e)-PV, (e)-wind**).

Comparison of wRP_NC60 and wo_NC60 showed that both NPV and Value of wRP_NC60 were higher than those of wo_NC60. As retiring existing thermal power plants were replaced by the latest GTCC in wRP_NC60, the spot price was higher than that of woRP_NC60 due to the initial cost of GTCC replacement (**Figure 3.10 (d)-PV, (d)-wind**). Though the greater VRE introduction resulted in lower CO2 emissions, the new GTCC contributed to CO2 emissions, thus lowering possible benefit.

As the financial support was insufficient in these cases, Company 2 was not encouraged to invest in VRE even though the expected NPV was positive (**Figure 3.10 (a)-PV, (a)-wind**). However, Company 2 may invest in VRE of 1,000 MW regardless of the strategies of Company 1 in case the top management has a lower RFP (Ref_CVaR) (**Figure 3.10 (c)-PV, (c)-wind**).



(a)-PV FIP Low (a)-Wind FIP Low

(b)-PV FIP Low (b)-Wind FIP Low

(c)-PV FIP Low (c)-Wind FIP Low

(d)-PV FIP Low (d)-Wind FIP Low

(e)-PV FIP Low (e)-Wind FIP Low

Figure 3.10. Results of different strategies of Company 1 with low FIP: **(a)** Expected NPV with Standard Deviation, **(b)** Value in case of high RFP, **(c)** Value in case of low RFP, **(d)** Spot price and **(e)** CO_2 emission.

3.3.3 Effect of VRE Mixture (Case 5 & 6)

Figure 3.11 shows the results when Company 2 mixed the capacity of PV and wind for investment. The left side of the figure represents an evaluation with low FIP, while the right side represents one with high FIP. In the case of low FIP, even though Company 2 mixed the capacity of PV and wind, few differences were observed in the expected NPV and value yielded by the mixture of PV and wind, and the effect of the mixture on the decision made by Company 2 was limited (**Figure 3.11 (a)- FIP low, (b)- FIP low**). However, Company 2 invested in 1,000 MW VRE regardless of the ratio of PV to wind in case the top management had a lower RFP (Ref_CVaR) (**Figure 3.11 (c)-FIP low**), a trend that is similar to that of the results in Sections 3.3.1 and 3.3.2.

On the other hand, in case of high FIP, when Company 2 adopted strategies to make a balanced investment in PV and wind, investment in VRE could be expedited compared to the strategies of PV or wind only (**Figure 3.11 (a)-FIP high, (b)-FIP high, (c)-FIP high**). The expected NPV and Value of MIX1(PV:Wind = 1:1), MIX2(PV:Wind = 7:3), and MIX3(PV:Wind = 3:7) were higher than those of PV_ONLY and WIND_ONLY; MIX3(PV:Wind = 3:7) was especially optimum. Comparison of MIX3(PV:Wind = 3:7) and WIND_ONLY showed that expected NPV and Value of the 7,000 MW investment were the highest for MIX3(PV:Wind = 3:7) and those of 5,000 MW for WIND_ONLY. We observed the standard deviation of MIX3(PV:Wind = 3:7) to be lower, and that of CVaR of MIX3(PV:Wind = 3:7) to be higher than those of WIND_ONLY. As the standard deviation represents the uncertainty of the investment and CVaR expresses risk, VRE with a well-balanced mixture reduced the uncertainty and risk in investment. This could result in the increased capacity of VRE introduction (**Figure 3.11 (d)-2, (e)-FIP high**). In the case of MIX3(PV:Wind = 3:7), upon comparing 5,000 MW to 7,000 MW investment, the expected NPV was observed to increase from 610.7 billion yen at 5,000 MW to 611.0 billion yen at 7,000 MW (+0.05%: almost the same) (**Figure 3.11 (a)- FIP high**), the Value with Ref_EXP from 78.0 to 79.1 (+1.4%) (Figure 10 (b)- FIP high) and the Value with Ref_CVaR from 97.1 to 100.4 (+3.4%) (**Figure 3.11 (c)- FIP high**). This implies that Company 2 may select a greater capacity of VRE than the NPV optimum capacity when it tries to invest in both PV and Wind in a balanced manner and the middle management gives a negative framing to the top management.

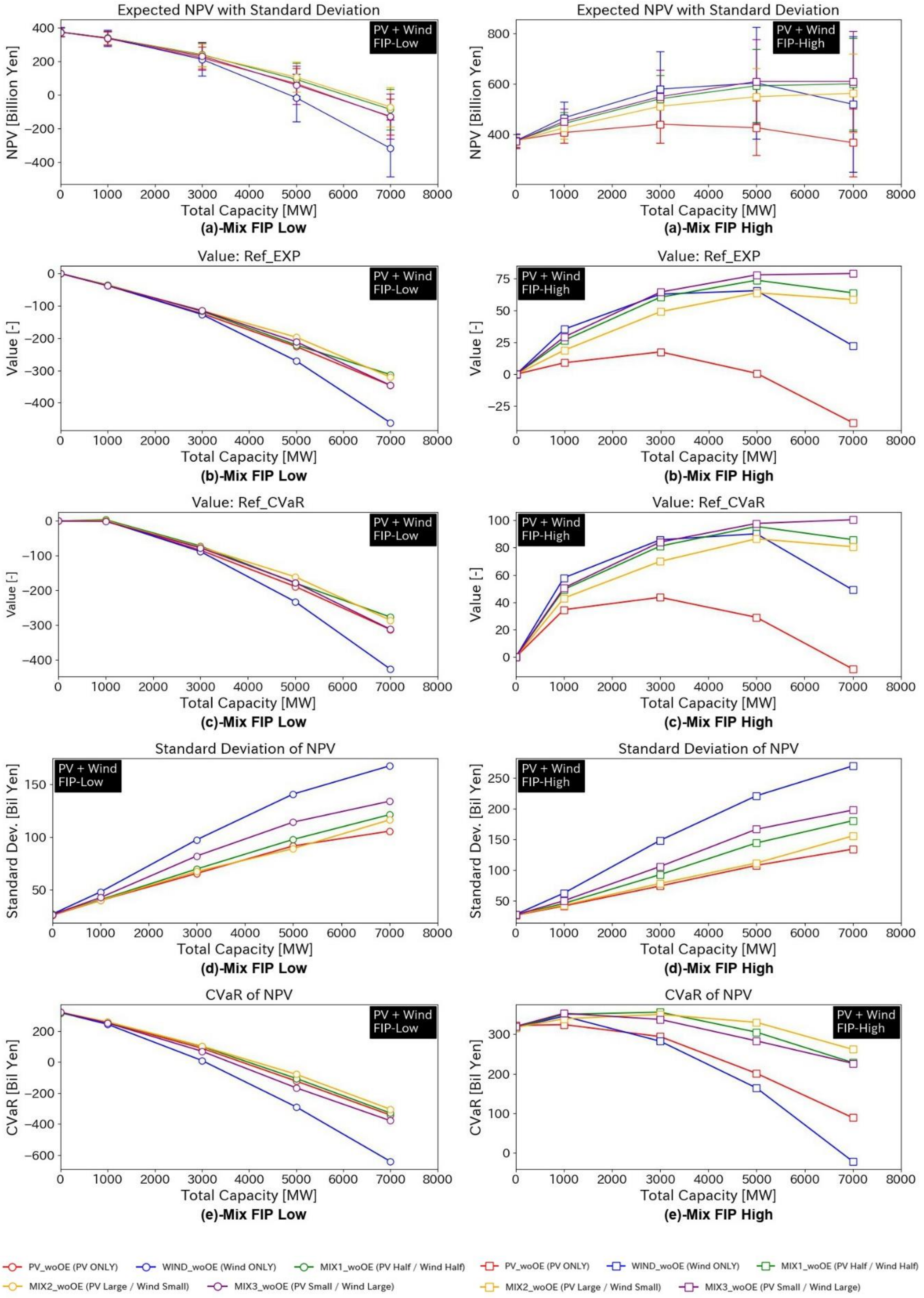


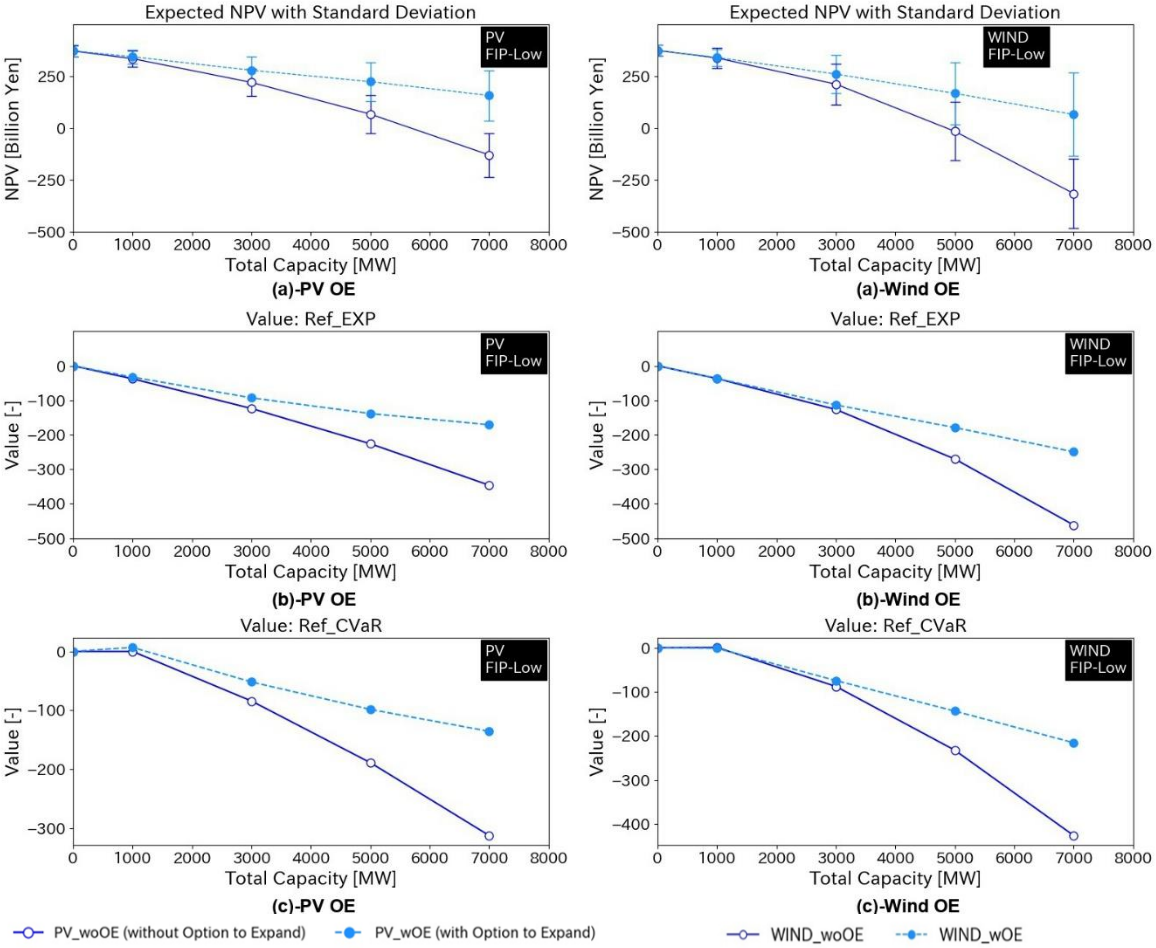
Figure 3.11. Results of Mixture of VRE: **(a)** Expected NPV with Standard Deviation, **(b)** Value in case of high RFP, **(c)** Value in case of low RFP, **(d)** Standard deviation of NPV and **(e)** CVaR of NPV.

3.3.4 Effect of Option to Expand in Cases 7, 8, 9, and 10

Figure 3.12 shows the results of the case “without” the option to expand (PV_ONLY, WIND_ONLY) and that “with” the option (PV_OE, WIND_OE) to expand in the case of low FIP. Company 2 was expected to simultaneously decide on investment in the entire capacity of VRE in 2025 and the case of PV_ONLY / WIND_ONLY. On the other hand, Company 2 decided to invest in the first half of VRE in 2025 and had the option of expanding the second half in 2030 in the case of PV_OE/WIND_OE.

In the scenario with Low FIP, the option to expand was found to result in a larger expected NPV and Value compared to the case without an option to expand because Company 2 could put the decision on hold until they reduced the risk of investment. However, as the Value for all cases with Ref_EXP (high RFP) was negative, Company 2 would not invest in additional VRE. Nevertheless, if the middle management could shift the RFP of the top management to Ref_CVaR (low RFP), the option to expand would possibly encourage the top management to invest in a small amount of VRE because the Value of 1,000 MW with Ref_CVaR was slightly positive (**Figure 3.12 (c)-PV**).

On the other hand, the scenario with high FIP provided the opposite trend, as shown in **Figure 3.13**; the option to expand reduced both expected VRE and Value and did not promote investment in VRE. This is simply because a relatively earlier investment yields considerably more income if enough financial support for VRE is expected.



(a)-PV OE

(a)-Wind OE

(b)-PV OE

(b)-Wind OE

(c)-PV OE

(c)-Wind OE

Figure 3.12. Results of option to expand in case of low FIP: **(a)** Expected NPV with Standard Deviation, **(b)** Value in case of high RFP and **(c)** Value in case of low RFP.

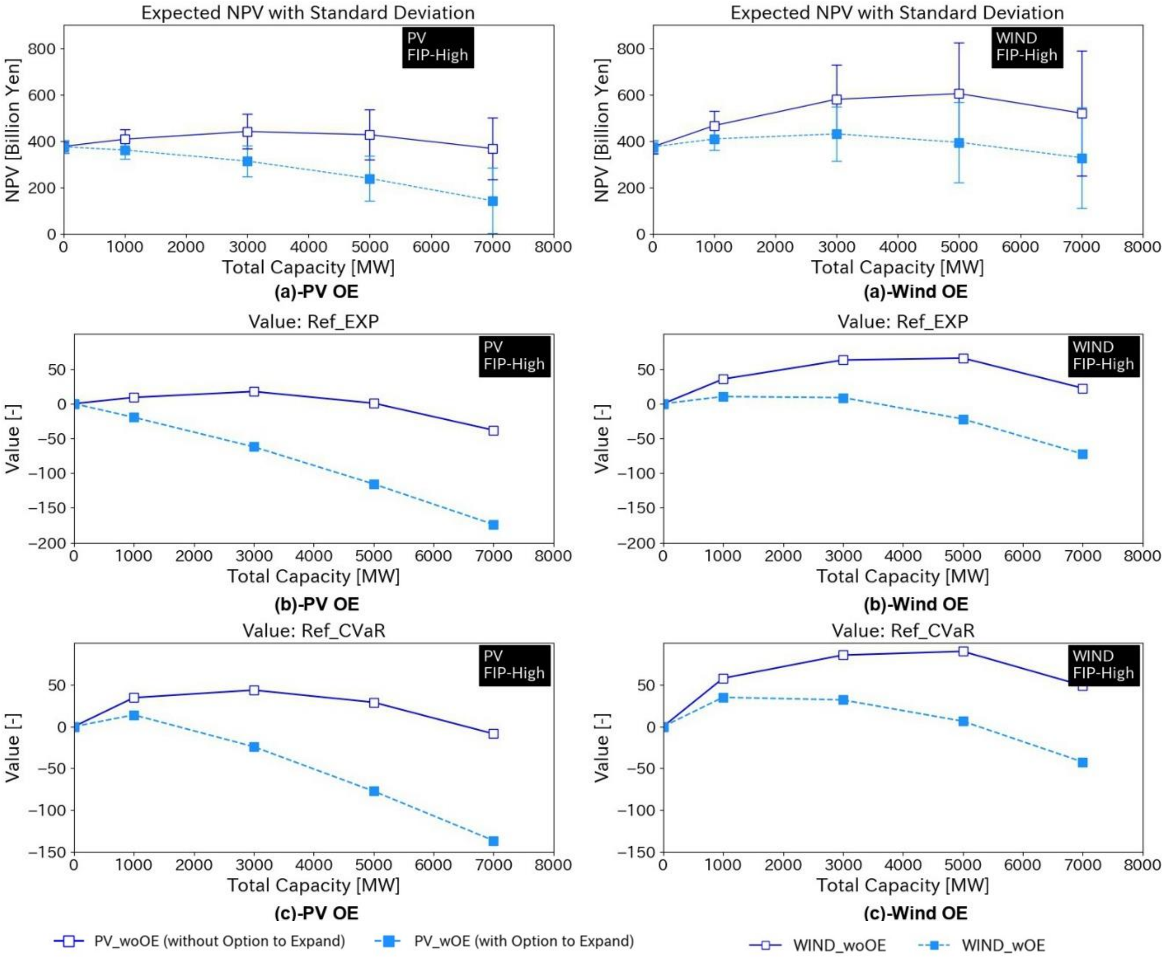


Figure 3.13. Results of option to expand in case of high FIP: **(a)** Expected NPV with Standard Deviation, **(b)** Value in case of high RFP and **(c)** Value in case of low RFP.

3.4 Conclusions

In this study, it was highlighted that there have not yet been sufficient discussions on non-normative decisions of companies in the field of power generation, even though the decisions of these companies could not always be rational under uncertainty. Therefore, we designed a novel framework to model the decision-making process by RE companies, as shown in Figure 1 because the conventional NPV approaches do not reflect the non-normative perspectives of decision-makers. A behavioral decision-making model was also developed based on the framework design to examine the decisions of the RE companies under uncertainty, as described in **Figures 3.2 and 3.3**. From the analysis of the simulation results based on the developed model, we obtained the following important information on RE company decisions with respect to future investment compared to the conventional NPV approach.

First, in the case where high financial support is expected, and the RE company (Company 2) plans to invest in either PV or wind, the company may decide to make an investment decision that is below the economically optimum capacity gained by the highest expected NPV due to income uncertainties of large-scale VRE introduction (graphs with FIP-High in **Figure 3.8**, Section 3.3.1). This result is consistent with the fact that companies could be more conservative in capital investments under uncertainty in reality [71]. Heavy investments in either PV or wind may become a damper of large-scale VRE introduction even though the high financial support attempts to expedite investments from a behavioral decision point of view.

Second, in contrast with the above point, in the case where high financial support is predicted and Company 2 attempts to make a balanced investment in both PV and wind, they possibly decide to invest in VRE that exceeds the capacity of the highest expected NPV (graphs with FIP-High in **Figure 3.11**, Section 3.3.3). This is because the balanced mixture of VRE maintains the increment in income uncertainties, and the risk is relatively smaller when the total VRE capacity increases. Some analyses in previous studies suggest that investments in both PV and wind reduce uncertainty and risk [127] and are economically preferable as renewable build-up pathways [128]. Modern portfolio theory also supports this result that an appropriate mixture ratio of PV to wind reduces the risk in VRE investment [129]. In addition, it was observed that the balanced mixture of PV and wind encourages RE investors, and the preferable capacity can be greater than the result obtained by the conventional NPV method, though the capacity to identify this investor behavior needs further verification from real-world case studies. Considering the results of the first and second points above, we suggest that governments implement policies to expedite investments in both PV and wind in addition to offering adequate financial support. In addition, the influence of the RFP difference is relatively small in the case of high financial support.

Third, in the case where low financial support is anticipated and the middle management emphasizes the “risk” in their suggestions, the top management may decide to invest in a small amount of VRE even though no investment (0 MW) earns the highest expected NPV (FIP-low cases in **Figure 3.9**, Sec. 3.3.1). That is, the top management could progress in VRE investment if they have a relatively lower RFP owing to the influence of the middle management. We observe a similar trend in different scenarios: regardless of the strategies of the competitor (Company 1; FIP-Low cases in **Figure 3.9**, Sec. 3.3.2), the mixture ratio of PV to wind (FIP-Low cases in **Figure 3.11**, Sec. 3.3.3), and the option to expand (in **Figure 3.12**, Sec. 3.3.4). As shown by a previous questionnaire survey, RE investors were sensitive to influence by peers [64], and the RE investor's behavior in the survey supports the simulation results by the model developed here. In other words, our study shows that the top management could be more aggressive in RE investments if surrounding peers emphasize the risk of investment when financial support is lower. In this study, we should mention that decision-makers are sensitive to the difference in RFP in case of low financial support in contrast with the first and second point discussed above.

In summary, we examined the behavior of RE companies in VRE investment decision using the developed model based on the designed framework and concluded that, compared to the optimal results yielded by the conventional NPV approach, (1) heavy investments in either PV or wind lead to reduced VRE capacity in the case of sufficient financial support, (2) balanced investment in both PV and wind results in increased VRE capacity in the case of sufficient financial support, and (3) suggestions that decrease RFP of the decision-makers expedite a small amount of VRE investments despite the insufficient financial support.

Despite the significant valuable results obtained from this study and the contribution that will be made by the emphasis on the proposed novel framework to the future analysis of the decision-making of VRE investment in the spot price market, certain conditions that may affect the results of this study are worth mentioning for the sake of future studies.

- Though renewable power generation companies were consolidated into Company 2 for simplicity, each renewable power generation company in the region may interact in reality. Also, though the strategies of Company 1 were given by some scenarios in this study, the interaction between the decisions of Company 1 and the RE companies need to be considered in future work.
- In this study, only two types of RFPs were defined as influence from suggestions by the middle management for simplicity: Ref_EXP (higher RFP) and Ref_CVaR (lower RFP) for simplicity. However, as mentioned in the framework of Section 3.2.1, there should be several factors influencing the RFP of the top management other than suggestions from the middle management, such as personal and exogenous influence. We should examine how the other non-normative perspectives affect the decisions made by the RE company.
- Kahneman and Tversky's approach [46,47] was used here to quantitatively express the non-normative perspective of RE companies in the decision-making model. However, since there could be other approaches for the non-normative perspective, these should be investigated.
- Energy storage was not applied as an option for technology. As the timeframe of decision making in this study was 2020–2030, we expected the effect of energy storage to be limited. However, energy storage should be considered in further studies of VRE introduction as the energy transition, such as in the 2050s, on a larger scale.
- Electricity trade spot price and feed-in premium were the only financial support considered for VRE to simplify the spot price market model. As emerging electricity markets and financial supports, such as the capacity market, are still being discussed in Japan, the effects of such new systems need to be examined.

CHAPTER 4. Possibility of Companies` Energy Transition based on the Analysis of Financial and Business Reports

4.1 Introduction

This chapter represents the meso-scale perspective of the energy transition, which is subject to influence from the results of both macroscopic and microscopic perspectives. This study attempts to observe and overview how companies' past efforts in the energy transition are affecting the current situation of companies by quantitively analyzing management information and CO_2 emissions. The results of the analysis are expected to bring new knowledge on the energy transition of companies.

As introduced in Section 1.2.3, energy transitions have become an important element in the management of companies as major members of society. For example, some companies have obtained Science Based Targets (SBT) certification, which requires companies to set science-based CO_2 reduction targets [130] and some participate in RE100, in which companies commit to shift all of the energy consumption in their business to RE [131]. It is becoming more common for companies to seek to enhance corporate value from the perspective of de-carbonization and energy transition.

On the other hand, since the number of companies who participate in these frameworks related to energy transitions are still limited, identifying the commonalities among proactive companies in energy transitions could provide new knowledge regarding the transition to de-carbonization of companies. In order to determine the common aspects of the companies, the analysis of financial statements and management indices is effective because the company's management policies, decisions, and business activities are assumed to be reflected in these key documents and indices.

As shown in Section 1.2.3, there have been several previous studies focusing on companies' environmental management in the field of financial and management analysis [83–88]. However, most of the previous studies have focused on the correlation between corporate environmental management/social responsibility and financial performance. There are no studies that have attempt to identify the characteristics of companies that are proactive in de-carbonization and energy transition from financial and managerial analysis perspectives, especially in the Japanese market.

The study presented in this chapter aims to gain new knowledge on energy transition in companies by analyzing financial information and CO_2 emissions of companies listed on the First Section of the Tokyo Stock Exchange (TSE1) by extracting the characteristics of companies that are proactively shifting to RE, with a focus on whether they are certified by SBT and/or participating in RE100. Companies with a market capitalization of 25 billion yen or greater can be listed on the TSE1. This study is also unique in that it uses machine learning techniques for the analysis.

4.2 Methodology

4.2.1 Overview of the Evaluation Procedure

In this study, it is hypothesized that a company's decision making on energy transition to RE is reflected in the annual securities report [132] directly and indirectly, and it was attempted to extract characteristics of companies that are actively promoting decarbonization and energy transition. The annual securities report includes quantitative data such as financial statements and qualitative documentation such as "Perspectives of the business." This study is characterized by the use of both quantitative financial information ((A) quantitative information analysis) and qualitative business-related document information ((B) qualitative information analysis), which are analyzed by applying machine learning methods. Additionally, new indices of CO_2 emissions are introduced to the (A) quantitative information analysis.

4.2.2 Conditions for the analysis

(1) Scope of analysis

In this study, 248 companies were selected out of those listed on the TSE1, and the 248 companies have reported their CO_2 emissions in business to CDP as of FY2019, which is an international non-profit organization that evaluates corporate environmental efforts. As shown in **Figure 4.1**, 47 of the 248 companies have received Science Based Targets (SBT) certification for their greenhouse gas reduction targets, and 20 companies have participated in the RE100 program, which commits them to operate their business with 100% RE in the future. Fifteen companies have been certified by SBT and participated in RE100. In this study, the companies certified by SBT and/or participated in RE100 were positioned as "proactive companies for decarbonization and energy transition to RE." (Details for CDP, SBT, and RE100, see Sections 4.2.2 (3)-(5).)

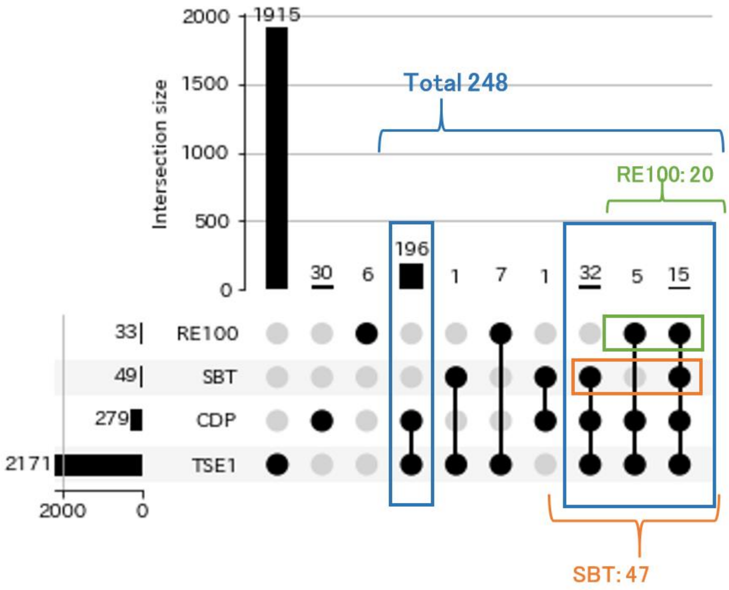


Figure 4.1. Scope of analysis

(2) Annual Securities Report

The Annual Securities Report is a document for disclosing corporate information to the public in Japan, and companies that are publicly traded on the stock exchange are required to submit the report to the Financial Services Agency at the end of each fiscal year. The financial statements are included in Section 5 of Chapter 1 in the Annual Securities Report. Also, Section 2 of Chapter 1 in the Annual Securities Report describes documented information on the business such as the "Summary of Business Performance," "Management Policy, Management Environment and Issues to be Addressed," and "Business Risks" in addition to quantitative information like "Production, Orders, and Sales,"

For (A) quantitative information analysis, the following financial indices were calculated from the financial statements and used in the analysis.

Index for Business Profitability

(A-1) Gross Profit Margin
(A-2) Net Profit Margin

Index for Return on Capital

(A-3) Return on Asset (ROA)
(A-4) Return on Equity (ROE)

Index for Risk

(A-5) Capital Ratio
(A-6) Current Ratio
(A-7) Free Cash Flow Margin (FCFM)

Index for Others

(A-8) Earnings per Share (EPS)

The average of the five years from FY2015 to FY2019 was used to calculate the financial indices. However, for companies that have only provided the information for less than five years, the average was taken of years for which information was available.

With regards to (B) qualitative information analysis, the text information contained in the "Management Policy, Business Environment and Issues to be Addressed" (Keiei-hoshin, Keiei-kankyo oyobi Taishosubeki Kadai tou) of the Annual Securities Report for FY 2018 was analyzed since it was assumed that a company's decisions on energy transition were most likely to appear in the section of "Management Policy, Business Environment, and Issues to be Addressed. " Since corporate management policies do not change significantly from year to year, the analysis is based on documentary information for the single year of FY2018.

(3) CDP and GHG protocols

Carbon Disclosure Project (CDP)is a non-profit organization based in London, UK, that collects, analyzes, and evaluates information on the environmental activities of companies around the world and makes the results available to institutional investors. CDP evaluates companies worldwide and gives scores to them based on replies to questionnaires in the fields of climate change, water resources, and forest resources. Though the CDP report [133] includes various information, CO_2 emissions of each company from the climate change report are used as one of the parameters to evaluate corporate activities since this study focuses on the energy transition of companies to a decarbonized society.

The Greenhouse Gas Protocol, A Corporate Accounting and Reporting Standard (GHG Protocol, hereafter) [134], which is an international greenhouse gas accounting standard. The GHG Protocol categorizes greenhouse gas emissions by businesses into three scopes;

Scope 1: Direct GHG emissions

Scope 1 means greenhouse gases emitted directly from equipment (boilers, vehicles, etc.) owned and managed by companies. However, the amount of CO_2 emissions from biomass owned and managed by companies are excluded.

Scope 2: Electricity indirect GHG emissions

Scope 2 means greenhouse gases that companies account for indirectly emitted by purchasing electricity. the Scope 2 Guidance [135] specifies the details of the methodology for calculating the greenhouse gases associated with the use of electricity from external sources. (In Scope 2, electricity, steam, and heating/cooling are collectively referred to as the term "electricity.") The "location-based method" and "market-based method" are defined as the calculation method for Scope 2. The location-based method reflects the average emissions intensity of grids on which energy consumption occurs. Under the location-based method, CO_2 emissions of companies are calculated based on the average emissions intensity of grids, and procurement of low carbon electricity by the companies is not directly reflected in the emissions. On the other hand, the market-based method reflects emissions from the electricity that companies have purposefully chosen. CO_2 reduction is taken into account in the emissions if the companies procure low-carbon electricity and vice versa.

Scope 3 Other indirect GHG emissions

All indirect greenhouse gas emissions other than Scope 2 related to the company's activities.

As of FY 2019, 540 Japanese companies have presented information on their activities in the field of climate change to the CDP, of which 248 companies listed on the TSE1 have provided scope 1 and 2 CO_2 emissions. The 248 companies were included in the analysis of this study. Unless otherwise noted, “CDP” in the context of the group of companies means this 248 companies. **Table 4.1** shows the number of companies in each of the 17 industry sectors (TOPIX 17).

Since this study focuses on companies’ decision-making for de-carbonization and energy transition to RE, the following two new indices were defined using the CO_2 emissions in scopes 1 and 2 presented in the CDP climate report. The new CO_2 indices were used on top of the financial indices from financial statements for (A) quantitative information analysis.

New CO_2 Indices

(A-9) CO_2 Scope 2 Ratio

This is defined as the ratio of the CO_2 emissions of Scope 2 divided by the sum of the CO_2 emissions of Scopes 1 and 2. If the index is smaller than 50% it means the Scope 2 CO_2 emissions are less, and if the index is larger than 50% it means the Scope 2 CO_2 emissions are greater compared to the Scope 1 CO_2 emissions of the company.

(A-10) Carbon Dioxide on Asset (CDOA)

This is defined as the sum of the CO_2 emissions of Scopes 1 and 2 divided by the total assets. This index was set up to compare the CO_2 emissions of companies whose asset sizes are different.

As mentioned above, Scope 2 can be calculated via location-based and market-based methods. Some of the 248 companies have provided CO_2 emissions using both location-based and market-based approaches, and the others have presented either location-based or market-based. The market-based CO_2 emissions were used for the analysis, and the location-based CO_2 emissions were used only if the market-based CO_2 emissions were not available for the companies. 208 (84%) of the total 248 companies, 45 (96%) of the 47 SBT certified companies, and 17 (85%) of the 20 RE100 companies provided market-based CO_2 emissions [133]. In other words, more than 80% of the companies have presented market-based CO_2 in every group, and the CO_2 emissions used in this study generally reflect the strategies of each company for the energy transition, such as procuring low-carbon power sources.

(4) Science Based Targets (SBT)

The SBT is a joint initiative of the CDP, the United Nations Global Compact (UNGC), the World Resources Institute (WRI), and the World Wide Fund for Nature (WWF), which aims to ensure that the global greenhouse gas emissions are consistent with a global target leading to well below a temperature increase of 2°C compared to pre-industrial levels. Companies must reduce Scope 1 and 2 greenhouse gases emitted over a period of 5 to 15 years, and the companies are recommended to reduce CO_2 emissions consistent with the 1.5°C target [130]. 47 SBT approved companies are analyzed and have presented CO_2 emissions for Scope 1 and 2 to CDP as of FY 2019. When "SBT" or "SBT Approved" are referred to in this study, these indicate the 47 companies unless otherwise noted.

As shown in **Table 4.1**, Though SBT Approved companies are found in a relatively wide range of industries, especially “CONSTRUCTION & MATERIALS” and “ELECTRIC APPLIANCES & PRECISION INSTRUMENTS” are the major industries in Japan. However, globally, there are many SBT approved companies in industries of the foods, electric power & gas, energy resources, and IT & services [136], which are different from the major industries in Japan. This implies that the characteristics of SBT approved companies (or companies that seek SBT approval) may differ by country or region.

(5) RE100

RE100 is an international initiative managed by The Climate Group, which is an international environmental non-profit organization, in partnership with CDP. It requires that participating companies commit to using 100% RE for their electricity in their business operations. The criteria for joining RE100 [131] include that companies are considered influential, corporate operations are defined according to GHG protocol, and companies are required to report annually through either the spreadsheet prepared by RE100 or the CDP questionnaire. Companies are required to have a business strategy to achieve 100% RE in their business by 2050, with 60% RE by 2030 and 90% by 2040 as a minimum requirement. However, companies that generate a large part of their revenue from renewable or non-renewable power, either directly or indirectly, will not be eligible to participate in RE100 unless they meet special requirements. In other words, it should be noted that efforts on energy shift of energy-intensive companies may be excluded from evaluation in RE100 Approved companies.

As of FY 2019, 33 Japanese companies are participating in RE100, of which 20 companies listed on the First Section of the Tokyo Stock Exchange that present CO_2 emissions in scope 1 and 2 to CDP were included in the analysis. When "RE100" or "RE100 Joined" are referred to in this study, these indicate the 20 companies unless otherwise noted. As **Table 4.1** shows, many of the companies participating in RE100 are in “RETAIL TRADE,” “CONSTRUCTION & MATERIALS,” and “ELECTRIC APPLIANCES & PRECISION INSTRUMENTS” in Japan. However, globally, many financial companies are participating in RE100, which is different from major industries in Japan. This implies that the characteristics of RE100 joined companies may differ by country or region [137].

When a company procures electricity generated by RE, there are three major ways: (1) on-site power generation at the company’s site, (2) power purchase contract with renewable power producers, and (3) acquisition of energy attribute certificates (e.g., green energy certificates) [138]. Most of the RE100 Joined companies are expected to mix these approaches to procure electricity of RE. At least nine of the 20 in RE100 Joined companies clearly state that they utilise on-site power generation, for example, by installing PV panels in their own sites [137].

Table 4.1. Number of companies in each industry, categorized in CDP, SBT Approved, and RE 100 Joined

TOPIX 17	Number of Companies		
	CDP	SBT Approved	RE100 Joined
ENERGY RESOURCES	3	0	0
REAL ESTATE	2	1	0
PHARMACEUTICAL	12	4	0
COMMERCIAL & WHOLESALE TRADE	3	0	0
RETAIL TRADE	8	3	4
CONSTRUCTION & MATERIALS	21	8	5
IT & SERVICES, OTHERS	19	5	2
MACHINERY	17	3	0
RAW MATERIALS & CHEMICALS	36	5	1
AUTOMOBILES & TRANSPORTATION EQUIPMENT	17	0	0
TRANSPORTATION & LOGISTICS	11	2	0
FINANCIALS (EX BANKS)	11	1	2
STEEL & NONFERROUS METALS	9	1	1
BANKS	7	0	0
ELECTRIC POWER & GAS	6	0	0
ELECTRIC APPLIANCES & PRECISION INSTRUMENTS	46	10	5
FOODS	20	4	0
Total	248	47	20

4.2.3 Analysis Procedure by k-means++ Method ((A) Quantitative Information Analysis)

The financial and CO_2 indices of the companies, defined in Section 4.2.2, were analyzed by clustering, which is one of the typical methods of unsupervised machine learning. Clustering is the division of a set of objects of analysis into subsets that satisfy internal coupling and external separation, and each subset is called a cluster. In this study, the following two cases of clustering were conducted.

Case 1.

Analysis based solely on financial indices from financial statements (Indexes from (A-1) to (A-8)

Case 2.

In addition to the financial indices, the CO_2 indices were applied (Indexes from (A-1) to(A-10))

Figure 4.2 shows the analysis flow of the quantitative information in this study. The analysis was performed via the following steps:

Step 1: Input of Features

Necessary information was collected from the Annual Securities Reports and the CDP climate change reports. Each index was calculated and entered as a feature in the clustering.

Step 2: Standardization of the Features

Standardization was performed so that the mean and standard deviation of each feature was 0 and 1, respectively, in order to optimize the distance scale of features. This is to avoid the influence of features with a wide range become dominant in the clustering.

Step 3: Dimensionality Reduction of Features

Since Case 1 and Case 2 had high-dimensional features of 8 and 10 dimensions, respectively, principal component analysis (PCA) was performed to reduce the dimensionality of the features. Dimensionality reduction for high-dimensional features was expected to improve the prediction performance and reduce the computational load. In PCA, for n-dimensional data, dimensionality reduction is achieved by projecting the n-dimensional data into a new sub-space with k-dimensional axes (principal components of k-dimensional data, $n \geq k$), which have the largest dispersion of data. In this study, dimensionality was reduced to the 3-dimensional principal components by PCA in both Cases 1 and 2. (See Appendix C.2 for results of principal component analysis.)

Step 4: Clustering

Clustering with the k-means++ method [139] was performed on the companies by using the 3-dimensional principal components of each company, which were obtained in Step 3. The k-means++ method is an application of the k-means method [140], which classifies data for minimizing the sum of the squared Euclidean distances between the center point and the data in each cluster.

The k-means++ method was selected in this study since the method is relatively good at dealing with large datasets due to the simple algorithm; the method is good at clustering a large number of companies' information [141], as in this study. In this study, we decided to cluster both cases 1 and 2 into six clusters. (See Appendix C.3 for the selection of the number of clusters.) The scikit-learn, which is one of the machine learning libraries in Python, was used for PCA and k-means++.

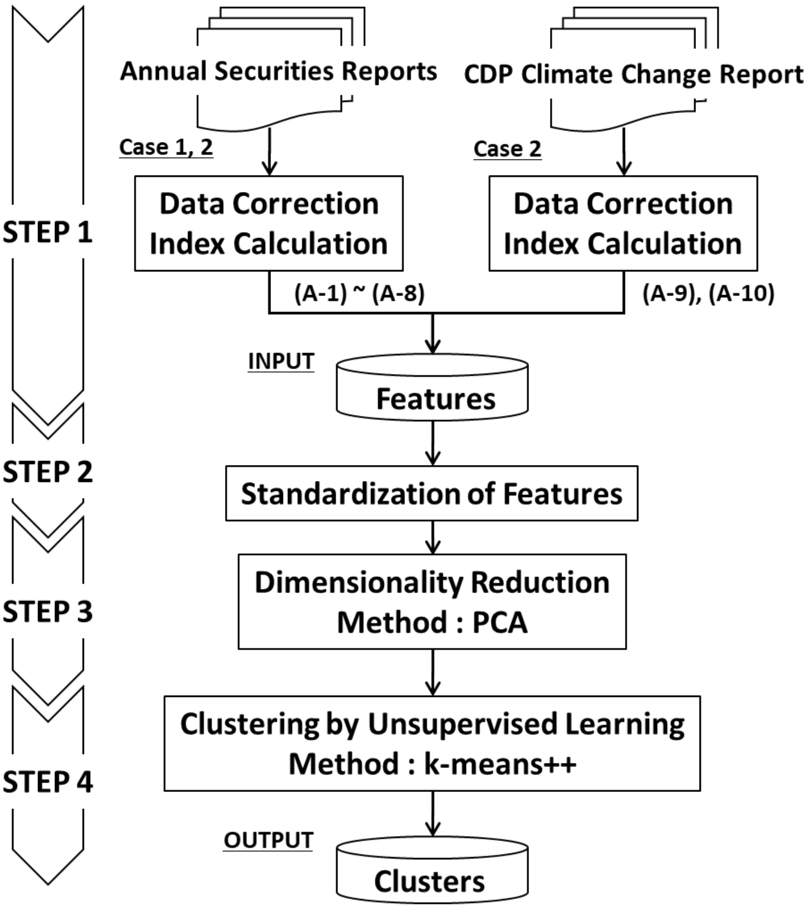


Figure 4.2. Analysis flow chart of quantitative information

4.2.4 Analysis Procedure by TF-IDF Method ((B) Qualitative Information Analysis)

The Term Frequency–Inverse Document Frequency (TF-IDF) method was applied, which is one of the methods to quantitatively evaluate the importance of words in documents, to the analysis of document information of companies. **Figure 4.3** shows the analysis flow of the qualitative information in this study, and the analysis is performed via the following steps:

Step 1: Input of Document Data

Document data described in the section of "management policies, business environment, and issues to be addressed" from each company's Annual Securities Report was collected, and pre-processed to remove unnecessary symbols, etc.

Step 2: Word Segmentation (Wakachi-Gaki Process)

Only nouns were extracted from the pre-processed document information, and if the nouns were consecutive, they were treated as compound nouns. The Wakachi-Gaki process was to give a separation between words in documents of languages that do not have a separation between words, such as Japanese.

Step 3: Development of BoW Model

Since textual data cannot be processed by a computer as is, the number of occurrences of each word in the segmented documents was counted in the segmented documents and converted into a feature vector for calculations in the computer. The data set of feature vectors are called a BoW Model (Bag of Words).

Step 4: Calculation of Term Frequency and Inverse Document Frequency

Term Frequency (TF) was calculated for each word based on the BoW model. TF is defined as the sum of the number of occurrences of each word divided by the sum of the number of occurrences of all words [142].

The IDF value is defined as the logarithm of a figure given by the total number of documents is divided by the number of documents in which each word appears [143]. The IDF value represents the rarity of each word. The formulation of TF and IDF is in Appendix C.1.

Step 5: Calculate the importance of the word

It is difficult to judge whether each word is an important word for the document by the TF value, which represents the frequency of the word. For example, although the frequency of occurrence (TF value) of "our company (group)" or “we” are high, it is not considered to be an important word in understanding the characteristics of the text information since these words are commonly used words. Therefore, the TF-IDF method [144] was applied. The TF-IDF of each word is given by multiplying its TF value by the IDF value, and it is expected that a word with a higher TF-IDF value is more important for the document.

Janome was used, which is a morphological analysis library for the Japanese language in Python, to perform the word segmentation process, and scikit-learn was applied, a machine learning library, to construct the BoW. The formulation of TF- IDF is in Appendix C.1.

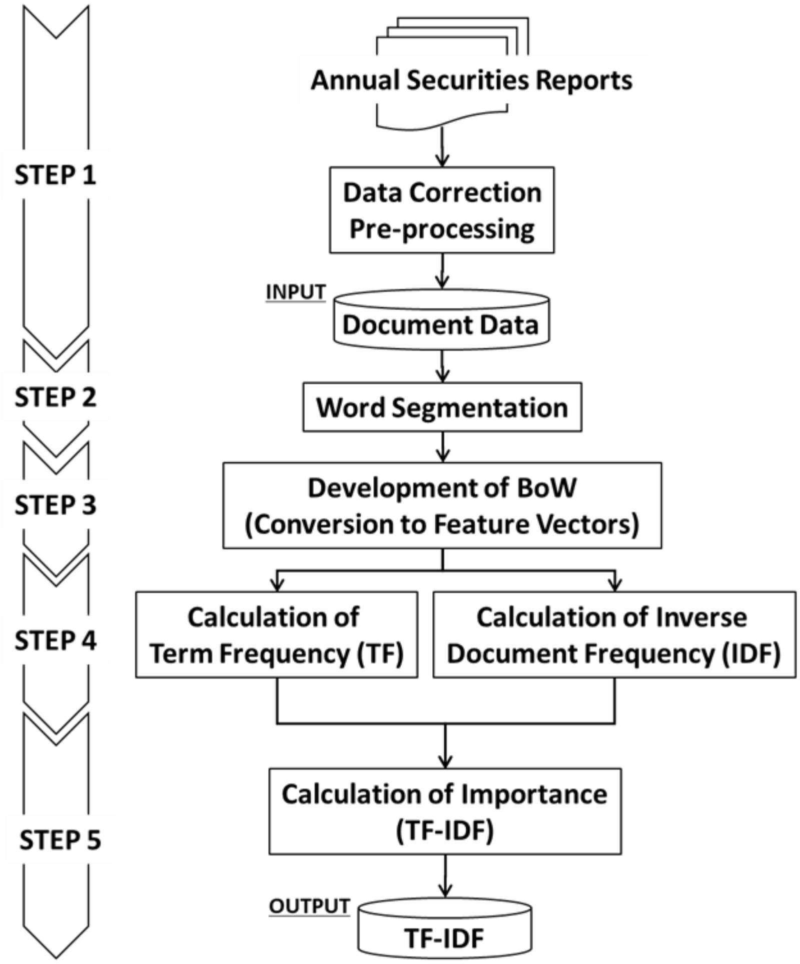


Figure 4.3. Analysis flow chart of qualitative information

4.3 Results

4.3.1 Analysis Results by k-means++ Method ((A) Quantitative Information Analysis)

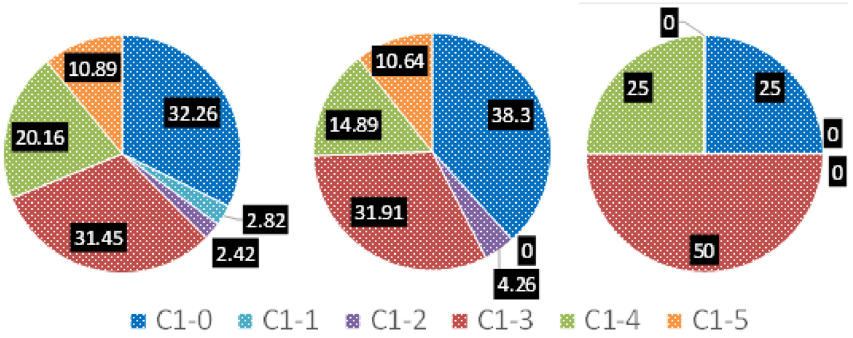
(1) Overview of clustering results

Figure 4.4 shows the clustering results for Case 1. The “CDP” represents the results of all 248 companies analyzed. Taken from the results of all 248 companies, the “SBT Approved” represents the results of 47 companies certified by SBT, and the “RE100 Joined” describes the results of 20 companies participating in the RE100 as well. The numbers in the pie chart show the percentage of companies in each cluster. In the legend, "C1-0" means cluster 0 in case 1, and the same is true for the other legends.

In Case 1, as **Figure 4.4** shows, clustering results for all the companies (“CDP”) were well-balanced even though companies in Cluster 0 and 3 were the largest (**Figure 4.4 (a)**). In the case of SBT Approved, companies in Cluster 0 were greater, and also in Cluster 4, although the trend was similar to that of the total set of companies (**Figure 4.4 (b)**). With regards to the RE100 Joined, 50% were in Cluster 3 and

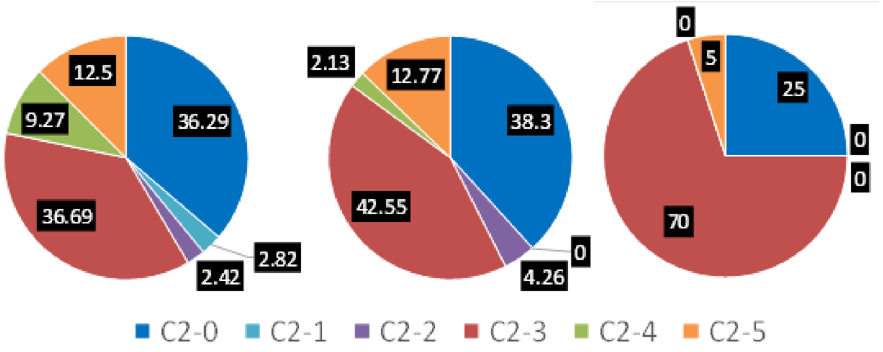
25% each in Cluster 0 and 4, which was different from the trend for the entire group of companies (**Figure 4.4 (c)**). These results suggest that SBT Approved and RE100 Joined companies tend to be distinctive in their financial indices, particularly for RE100 Joined companies.

Figure 4.5 shows the clustering results for Case 2. The result for all companies was relatively well-balanced, although there were slightly more companies classified into Clusters 0 and 3 than Case 1 (**Figure 4.5 (a)**). Most SBT Approved companies were classified into Clusters 0 and 3, and the ratio was greater than the result of the whole set of companies (**Figure 4.5 (b)**). The result of RE companies was more biased, and 70% of the companies were clustered in cluster 3 (**Figure 4.5 (c)**). That is, the clustering results for SBT Approved and RE100 Joined companies were more biased than those in Case 1. These results suggested that the introduction of CO_2 indices in addition to financial indices enabled the effective extraction of characteristics of companies that were proactive in energy transition. In the following sections, the analysis was focused on Case 2.



(a) CDP **(b)** SBT Approved **(c)** RE100 Joined

Figure 4.4. Clustering Result of Case 1: **(a)** CDP (all 248 companies), **(b)** SBT Approved (48 companies) and **(c)** RE100 Joined (20 companies)



(a) CDP **(b)** SBT Approved **(c)** RE100 Joined

Figure 4.5. Clustering Result of Case 2: **(a)** CDP (all 248 companies), **(b)** SBT Approved (48 companies) and **(c)** RE100 Joined (20 companies)

(2) Clustering results by industry (Case 2)

Table 4.2 shows the results of clustering by the industry for the 17 industry categories (TOPIX 17) in Case 2. For the whole companies ("CDP" in **Table 4.2**), Cluster 0 included many companies in the "MACHINERY," "RAW MATERIALS & CHEMICALS," "ELECTRIC APPLIANCES & PRECISION INSTRUMENTS," and "FOODS" sectors. Cluster 1 classified only "BANKS," and Cluster 2 was characterized to include three "TRANSPORTATION & LOGISTICS" companies (three of them were Marine Transportation). Cluster 3 was the largest cluster, where companies of "CONSTRUCTION & MATERIALS," "FINANCIALS (EX BANKS)" were classified. Also, all companies of "COMMERCIAL & WHOLESALE TRADE" were in Cluster 3. Cluster 4 featured "ENERGY RESOURCES" and "ELECTRIC POWER & GAS." Cluster 5 included many companies of "ELECTRIC APPLIANCES & PRECISION INSTRUMENTS," and the cluster was especially characterized by "PHARMACEUTICAL."

With regard to the SBT Approved companies ("SBT Approved" in **Table 4.2**), Clusters 0, 2, and 5 showed almost the same trend as the whole set of companies. On the other hand, more companies were classified as Cluster 3 compared to the results of all companies. In particular, 11 out of 31 (about 33%) of companies of "CONSTRUCTION & MATERIALS" were in Cluster 3 for the whole set of companies, while 5 out of 8 (about 63%) of the SBT Approved companies were in Cluster 3. Also, 11 out of 46 (about 24%) of "ELECTRIC APPLIANCES & PRECISION INSTRUMENTS" were in cluster 3 for the total set of firms, while 5 out of 10 (about 50%) of the SBT Approved companies were in this cluster.

Looking at the RE 100 Joined companies, most of the companies were clarified in Cluster 3 ("RE100 Joined" in **Table 4.2**). These suggested that characteristics of companies proactive in energy transition appeared in Cluster 3, although the type of industry could affect the clustering results.

Table 4.2. Clustering results by industry

TOPIX 17	Number of Companies																	
	CDP						SBT Approved						RE100 Joined					
Cluster	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5
ENERGY RESOURCES	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
REAL ESTATE	0	0	0	2	0	0	0	0	0	1	0	0	0	0	0	0	0	0
PHARMACEUTICAL	3	0	0	1	0	8	1	0	0	0	0	3	0	0	0	0	0	0
COMMERCIAL & WHOLESALE TRADE	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RETAIL TRADE	2	0	0	5	0	1	1	0	0	2	0	0	1	0	0	3	0	0
CONSTRUCTION & MATERIALS	4	0	0	11	5	1	1	0	0	5	1	1	1	0	0	3	0	1
IT & SERVICES, OTHERS	9	0	0	7	0	3	3	0	0	2	0	0	1	0	0	1	0	0
MACHINERY	10	0	0	6	0	1	2	0	0	1	0	0	0	0	0	0	0	0
RAW MATERIALS & CHEMICALS	14	0	1	8	6	7	3	0	0	1	0	1	1	0	0	0	0	0
AUTOMOBILES & TRANSPORTATION EQUIPMENT	7	0	0	9	0	1	0	0	0	0	0	0	0	0	0	0	0	0
TRANSPORTATION & LOGISTICS	0	0	3	6	2	0	0	0	2	0	0	0	0	0	0	0	0	0
FINANCIALS (EX BANKS)	1	0	0	10	0	0	0	0	0	1	0	0	0	0	0	2	0	0
STEEL & NONFERROUS METALS	2	0	0	5	2	0	0	0	0	1	0	0	0	0	0	1	0	0
BANKS	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ELECTRIC POWER & GAS	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0
ELECTRIC APPLIANCES & PRECISION INSTRUMENTS	25	0	2	11	0	8	5	0	0	5	0	0	1	0	0	4	0	0
FOODS	12	0	0	7	0	1	2	0	0	1	0	1	0	0	0	0	0	0
Total	90	7	6	91	23	31	18	0	2	20	1	6	5	0	0	14	0	1

(3) Clustering results by index (Case 2)

Figures 4.6, 4.7, and **4.8** show each cluster's distribution for each feature (index) in Case 2. The vertical axis of each figure is the features, and the horizontal axis is the clusters. The box plots in the figure show the distribution of each feature, where the blue box shows the distribution of the whole set of companies ("CDP"), the red box is the SBT Approved companies, and the green box is the RE100 Joined companies. The black dots in the figure represent the value of the feature of each company.

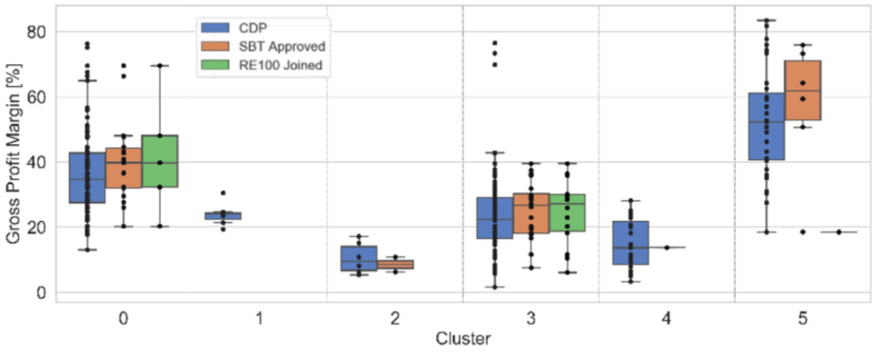
Clusters 0 and 3 were the clusters in which many companies were classified, and the gross profit margin, net profit margin, ROA, and ROE of these companies were found in normal ranges. When Cluster 3 was compared to Cluster 0, ROA, ROE, capital ratio, and current ratio were relatively lower. Cluster 3 included many SBT Approved, and RE 100 Joined companies, and this could be interpreted that companies proactive in energy transition did not always belong to the best cluster in terms of financial performance. This result implies companies that were proactive in energy transition either (i) saw qualitative value in their de-carbonization efforts rather than financial benefits, (ii) expected to earn financial benefit by energy transition, but remained in a normal financial performance as a result, or (iii) counting on long-term rather than short-term benefit. The scope 2 ratio of CO_2 emissions were relatively high for both Clusters 0 and 3, but the scope 2 ratio is particularly high for RE100 participants in Cluster 3. Besides, CDOA of the SBT Approved and RE100 Joined companies were lower values than those of CDP companies in each cluster. That is, companies proactive in energy transition were characterized by higher indirect CO_2 emissions relative to direct emissions and lower CO_2 emissions for company size.

Cluster 1 featured a very high FCFM. Although the net profit margin was high, ROA and ROE are relatively low, and the capital ratio and current ratio are low. This cluster included only "BANKS," and these results captured the financial characteristics of banks. This cluster had a very high scope 2 ratio and low CDOA, which also showed features of the industry of "BANKS."

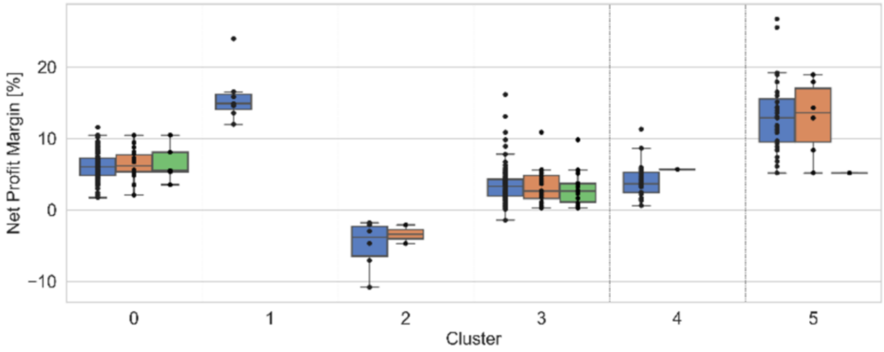
Cluster 2 had gross margins of less than 20% and negative net profit margins. As a result, ROA and ROE were also negative, especially ROE was lower than other clusters, which made the cluster unfavorable from the perspective of financial indices. With regard to the CO_2 indices, the Scope 2 ratio spread across a wide range, and the CDOA was high. Two companies in this cluster were SBT Approved, and zero companies joined in RE100. Companies with unfavorable financial performance might be relatively less proactive in energy transition or had difficulty satisfying the requirements for SBT approval and RE100 participation.

Cluster 4 was a cluster with high direct CO_2 emissions due to its low scope 2 ratio, and with high CO_2 emissions for company size. This cluster included electric utilities, airlines, steel companies, oil wholesale companies, etc. The cluster showed the characteristics of energy-intensive companies that earn income through energy consumption. Possibly, as mentioned in Section 4.2.2 (5), the efforts in energy transition of energy-intensive companies might be excluded from the evaluation of RE100 Joined. However, there were also few SBT Approved companies in this cluster. This suggested that, at least in the analyzed groups of companies, energy-intensive firms might be relatively less proactive in energy transition or had difficulty in satisfying the requirements for SBT approval. This result was in contrast to the fact mentioned in 4.2.2 (4), where many power and energy-related companies in the world were SBT approved.

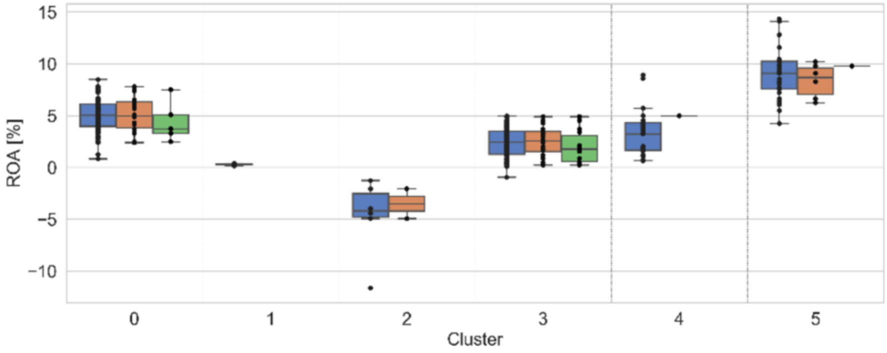
Cluster 5 had high gross profit margins, net profit margins, ROA and ROE, and high capital ratio and current ratio, making it an excellent cluster of companies in terms of financial performance. Also, the cluster had a relatively high scope 2 ratio and low CDOA in terms of CO_2. Although industry bias classified in this cluster might have affected the results, it was interesting to note that the number of SBT Approved and RE Joined companies was low among the financially excellent companies with low CO_2 emissions relative to company size.



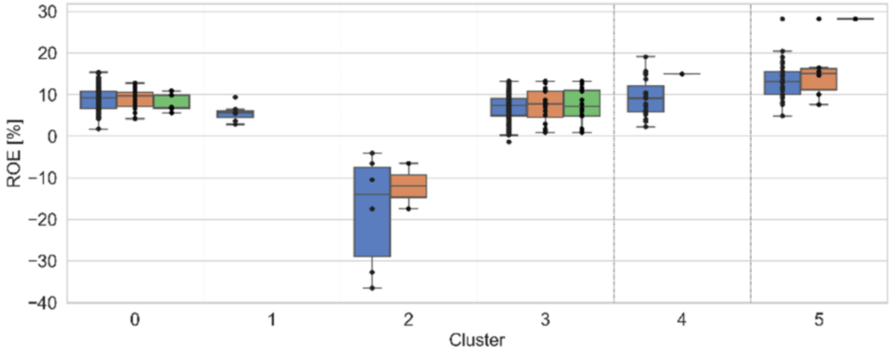
(a) Gross Profit Margin



(b) Net Profit Margin

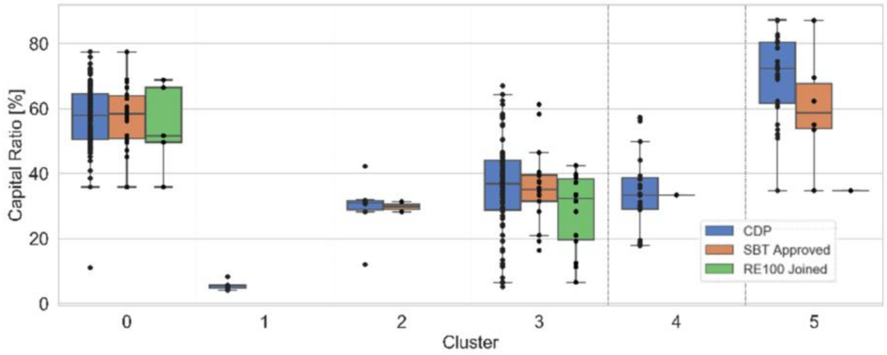


(c) ROA

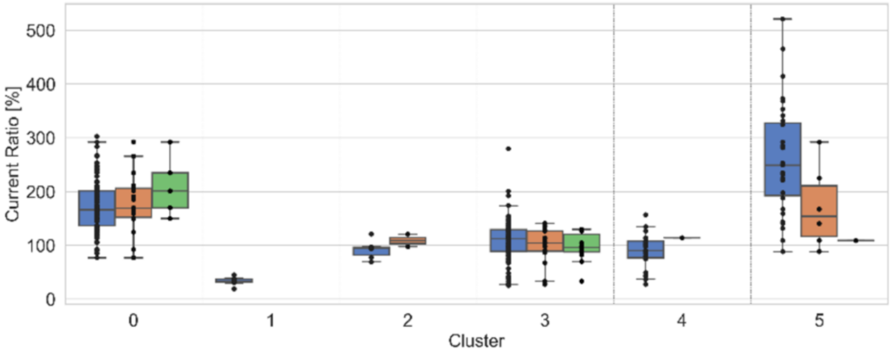


(d) ROE

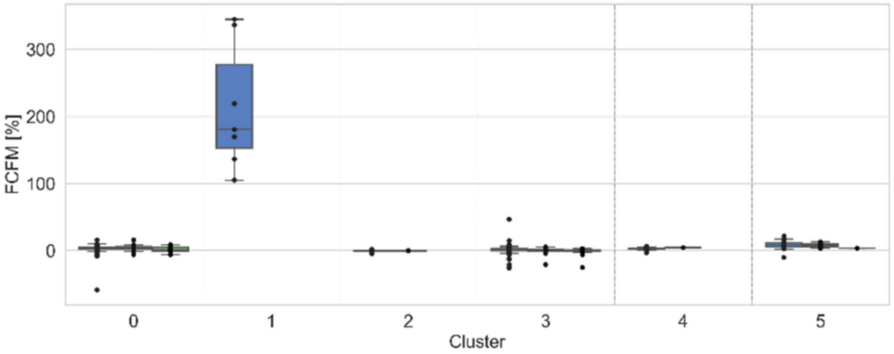
Figure 4.6. Clustering Result by indexes for profitability in Case 2: **(a)** gross profit margin, **(b)** net profit margin, **(c)** ROA, and **(d)** ROE



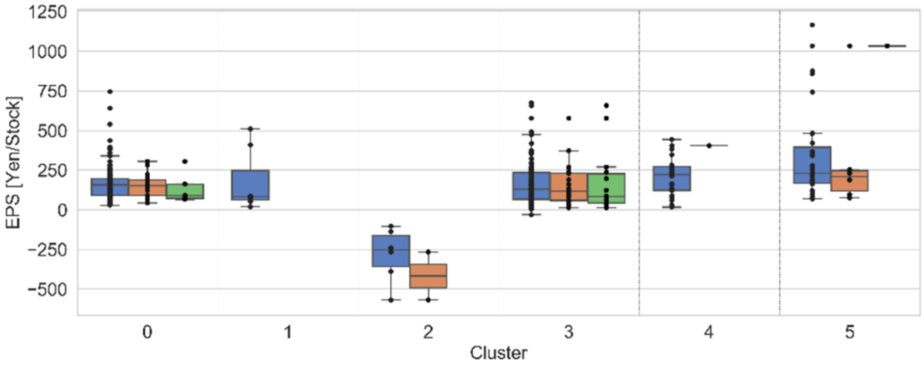
(a) Capital Ratio



(b) Current Ratio

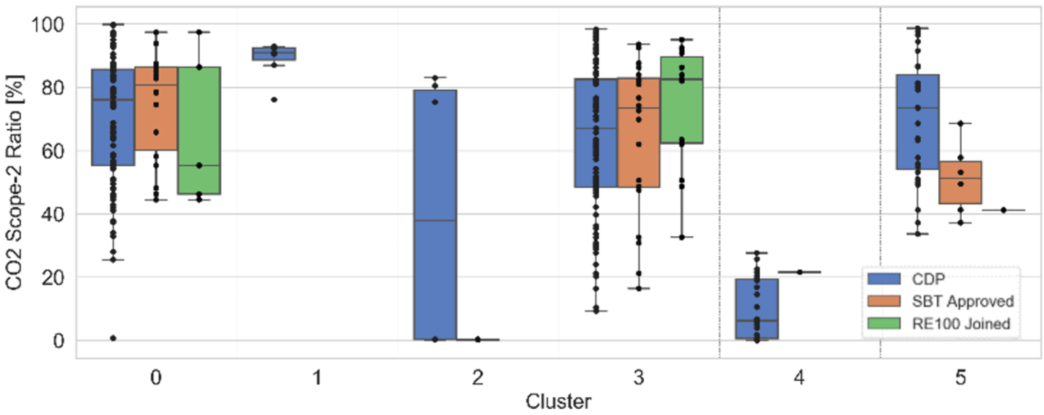


(c) FCFM

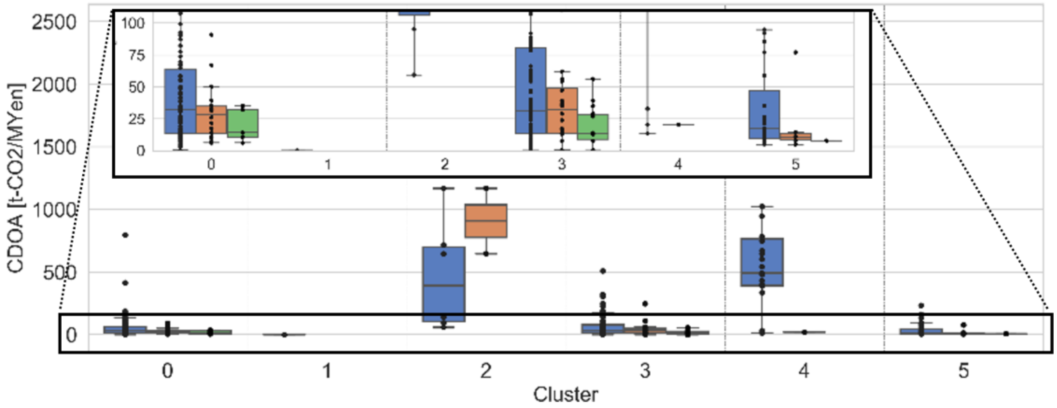


(d) EPS

Figure 4.7. Clustering Result by indexes for safety and other financial related in Case 2: **(a)** capital ratio, **(b)** current ratio, **(c)** FCFM, and **(d)** EPS



(a) CO_2 Scope 2 Ratio



(b) CDOA

Figure 4.8. Clustering Result by indexes for CO_2 emission in Case 2: **(a)** CO_2 scope 2 ratio and **(b)** CDOA

Figure 4.8. Clustering Result by indexes for CO_2 emission in Case 2: **(a)** CO_2 scope 2 ratio and **(b)** CDOA

4.3.2 Analysis Results by TF-IDF Method ((B) Qualitative Information Analysis)

Table 4.3 shows the top 30 words with the highest TF-IDF values in the documents of "Management Policy, Business Environment, and Issues to be Addressed, etc.". “CDP" represented the results in all 248 companies, "SBT Approved" were the results of the 47 SBT approved companies extracted from the results of all 248 companies, "RE100 Joined" were the results of 20 companies participating in RE100.

In the overall results for the companies (“CDP”), the most common words that appeared in the table were "Customers" and "Everybody," which are customer- and shareholder-related words, "Board" and "Medium Term Business plan," which are related to corporate management and organization, and "Joint Shareholders," "Scale Buying, " "Equity Warrant " and other stock-related words.

With regard to the SBT Approved companies, it was observed in the spreadsheet that their own company name, group names, “Main Brand” and “Marketing Activity,” which were words related to the company’s brand, were more frequently used. As described in Section 4.2.4, TF-IDF was calculated by multiplying the frequency of words by the rareness of the words. Therefore, the TF-IDF of a company's name tends to be higher in general since a certain company’s name could appear in the company’s document but not in other company’s documents. However, because SBT Approved companies dared to use their own company name and group name more often in their documents than general terms such as "our company" or “we,” it could be interpreted that words related to the company's brand were more important for SBT Approved companies.

In the RE100 Joined companies, it was found that there were many words tied to business strategies as important words such as "Strategic Field," "Growth Strategy," "Management Strategy," "Business Strategy," "Strategic Direction," etc. The CDP questionnaire, which was explained in section 4.2.2. (3), includes a question that "Have you incorporated climate change scenario analysis into your business strategy?". The 17 companies out of the RE Joined 20 companies (approx. 85%) answered that "we incorporate scenario analysis qualitatively, quantitatively, or both"; these percentages were greater than 140 companies out of the all 248 companies (approx. 56%) [133]. Considering the questionnaire on top of the IF-IDF analysis of this study, it could say that the RE100 Approved companies were more focused on their business strategy than other companies, and they could regard their business strategy as an important factor for their energy transition.

The words with a high TF-IDF might not necessarily directly reflect the company's decision-making on de-carbonization and energy transition since the section "Management policy, business environment and issues to be addressed" described not only de-carbonization and energy transition but also other business policies. However, though the 248 companies were relatively positive in decarbonization in general compared to other companies since the whole 248 companies provided CO_2 emissions to CDP, the TF-IDF analysis of SBT Approved and RE 100 Joined companies out of the 248 companies showed unique results. Therefore, it could be interpreted that companies proactive in energy transition were more aware of their "own brand" and "business strategy" than the other companies.

Table 4.3. Top 30 words given by TF-IDF analysis

Rank	**TF-IDF Top 30 Words**		
	CDP	SBT Approved	RE100 Joined
1	Customers (Okyaku-sama [Partially Hiragana])	Company A Group	Company B
2	Plan	Consolidated Group (Renketsu Group)	Housing (Jutaku)
3	Board (Tosha Torishimariyakukai)	Midterm Strategy (Tyuki Senryaku)	Strategic Field (Senryaku Bunya)
4	Joint Shareholders (Kabunushi Kyodo)	agp	Business
5	Scale Buying (Kibo Kaitsuke Koi)	Company B	lohaco
6	Policy (Taio Hoshin)	Board (Tosha Torishimariyakukai)	opa
7	Everybody (Minasama [Kanji])	Policy (Taio Hoshin)	Department Store
8	Countermeasures (Taiko Shochi)	Housing (Jutaku)	Policy (Taio Hoshin)
9	Scale Buyer (Kibo Kaitsuke-sha)	Company C Group	scope
10	Operation (Hatsudo)	Company D Group	Customer (Okyaku-sama [Partially Hiragana])
11	March Period (3 Gatsuki)	Outside Board Committee (Shagai Torishimariyaku Dokuritsu Iinkai)	Growth Strategy (Seityo Senryaku)
12	Midterm Buiness Plan (Chuki Keiei Keikaku)	Kirin Group	Climate Change (Kikou Hendo)
13	Independent Committee (Dokuritsu Iinkai)	Main Brand (Shuryoku Brand)	Resident (Nyukyo-sha)
14	Equity Warrant (Shinkabu Yoyaku Ken)	Value Creation Management (Kachi Sozo Keiei)	Management Strategy
15	Scale Buying Rule (Kibo Kaitsuke Rule)	scope	Business Strategy
16	Profit (Rieki)	operational excellence	Graphics (Gazou)
17	Large Scale Buying (Tairyo Kaitsuke Koui)	Operation (Hatsudo)	Task Force (Tokubetu Tyosa Iinkai)
18	Buyer etc. (Kaitsuke-sha Tou)	Focused Area (Tyuryoku Bunya)	Asset Succession (Shisan Keiho)
19	Midterm Business Plan (Tyu-kei)	Correction (Shusei)	Scale Buying etc. (Kibo Kaitsuke Tou)
20	Shareholders (Tosha Kabunushi)	Company E Group	Frontier
21	Board (Torishimariyaku Kai)	Owner (Shoyusha)	Home (Sumai)
22	Midterm Business Plan (Ji Chuki Keiei Keikaku)	lohaco	Recurrence Prevention Measures (Saihatsu Boshi Saku)
23	Recurrence Prevention Measures (Saihatsu Boshi Saku)	opa	Urban Development Strategy (Machizukuri Senryaku)
24	Everybody (Mina-sama [Partially Kanji])	Marketing Activity (Marketing Katsudo)	Global Strategy
25	Everybody (Mina-sama [Hiragana])	Countermeasures (Taiko Shochi)	Global Business
26	challenge	Everybody (Mina-sama[Kanji])	lixil behaviors
27	We (Watashi-tachi)	Midterm Management Policy (Chuki Keiei Hoshin)	Strategic Direction (Senryakuteki Houkousei)
28	Customers (Okyaku-sama [Kanji])	Company Foundation (Kigyo Kiban)	Final Report (Saishuu Houkokusho)
29	Large Scale Buying (Tairyo Kaitsuke)	Medical Needs (Iryo Needs)	Detached Housing (Kodate Juutaku)
30	Secom	Joint Shareholders (Kabunushi Kyodo)	Australia

4.4 Conclusions

This study identified the characteristics of 248 companies listed on TSE1 that are proactively shifting to RE by quantitively analyzing financial indexes and CO_2 emissions using the k-means++ method and document information of management policy with the TF-IDF method.

The analysis results of financial indexes show that the financial performance of SBT Approved and RE100 Joined companies are in the normal range or slightly below. Besides, the clustering results clarify that not only financially unfavorable companies and energy-intensive companies but also companies with high financial performance can be relatively less proactive in the energy transition. With regard to the analysis of CO_2 emissions, it became clear that SBT Approved and RE100 Joined companies had more massive indirect CO_2 emissions than direct CO_2 emissions in their business, and CO_2 emissions for company size were relatively small. Especially, these trends were clearly observed in the RE100 Joined companies.

The analysis results of management policy show that SBT Approved companies are more aware of their brand and that RE100 Joined companies are more conscious of their business strategy compared to all other analyzed companies.

In the conclusions of this chapter, from the perspective of financial and business analysis, this study provides the following findings regarding energy transition in companies;

1. From the financial profitability and safety analysis: companies that are proactive in energy transition have normal or slightly below financial performance. Not only financially unfavorable companies but also the financially excellent companies are not necessarily proactive in energy transition (Section 4.3.1, **Figures 4.6** and **4.7**).
2. From the analysis of CO_2 indexes: companies that are proactive in energy transition have more indirect emissions (external procurement) as a source of CO_2 emissions in their business operations compared to direct emissions. Besides, they have lower CO_2 emissions for the total assets (Section 4.3.1, **Figure 4.8**).
3. From the analysis of document information on management policies: SBT Approved companies tend to be more aware of their brand, and RE100 Joined companies show a trend to be more focused on their business strategy compared to other companies (Section 4.3.2, **Table 4.3**).

As mentioned above, this study provides useful knowledge on energy transition in companies. However, it should be aware that there are some limitations and issues in the study as follows;

- This study selected companies listed on the TSE1 that present their values of CO_2 emissions to the CDP in order to obtain certain information on CO_2 emissions for analysis on the same basis.

Therefore, the results do not capture the efforts of companies that do not present their CO_2 emissions to CDP, as well as foreign companies that are engaged in the energy transition.

- The analysis of financial and CO_2 of this study does not take into account differences in approaches of companies to de-carbonization (e.g., on-site power generation, acquisition of green energy certificates, etc.). Besides, differences in CO_2 emissions caused by direct and indirect energy consumption were not considered, as well.
- In the analysis of management policies, the importance of the words contained in the document information was assessed, but the results did not show the correlativeness between each word.

In particular, the first point of conclusions in this study implies that efforts on energy transition of companies may have to sacrifice their financial performance to a certain extent. Still, this fact seems to conflict with the fact that companies seek profits as profit organizations. Further investigation of this point is needed.

CHAPTER 5. Conclusions and Future Work

5.1 Discussions and Conclusions

This work aims to clarify the conditions that move companies forward to the energy transition under restrictions of existing infrastructure with multiple perspectives based on quantitative approaches. In order to draw conclusions on this work, the novel framework was designed (**Figure 1.3**) in Chapter 1, and Chapters 2, 3, and 4 obtained the following conclusions.

Chapter 2 took a role as the macroscopic perspective of the energy transition in a future-oriented approach. This chapter clarified that the large-scale introduction of VRE with the chronological replacement of retiring thermal power plants would contribute to reducing the total cost during the energy transition, as well as the amount of surplus electricity of RE. In other words, it was pointed out that the energy transition to RE with replacement of retiring thermal power plants and extending the lifetime of nuclear power plants could be a feasible and realistic scenario from a macroscopic economic point of view. With regard to technologies, the introduction of VRE during the energy transition had regional characteristics; PV would be introduced more in the region where the capability of power adjustment by gas-fired power generation is large, and wind power would be more in the region where the capability of power adjustment is small. Besides, in the scenario of replacing retiring power plants, hydrogen as an energy storage with inter-regional transportation, which means hydrogen produced by the surplus electricity in a region with larger RE introduction and transferred to another region with the greater hydrogen-fired GTCC capacity, can reduce the total cost, bridge the lack of reserve margin, and promote VRE introduction.

Chapter 3 represented the microscopic perspective of the energy transition in a future-oriented approach. This chapter designed the novel framework of the decision-making process by RE companies (**Figure 3.1**). It developed the behavioral decision-making model to examine the decisions of the RE companies under uncertainty (**Figures 3.2** and **3.3**). As per the simulation results, the scenario with the replacement of retiring thermal power plants and life extension of nuclear power plants was better from the RE company's income and CO_2 emissions point of view, which was consistent with the result of Chapter 2. Besides, it became clear that (1) heavy investments in either PV or wind resulted in decreased VRE capacity despite sufficient financial support, (2) balanced investments in both PV and wind yields a larger VRE capacity in cases sufficient financial support, and (3) co-worker's suggestions that lowered the decision-makers' RFP encourages VRE investments despite insufficient financial support.

Chapter 4 attempted to observe the influence of past and ongoing company's energy transition from meso-scale perspectives. From the financial performance point of view, companies proactive in energy transition had normal or slightly below financial performance. Besides, companies with high financial performance and energy-intensive companies could be relatively less proactive in the energy transition. As per the analysis of CO_2 emissions, companies proactive in energy transition had larger indirect CO_2 emissions than direct ones and less CO_2 emissions for the company scale. Besides, from the company's management perspective, companies proactive in energy transition are more aware of their "own brand" and "business strategy" than the other companies.

Table 5.1, **5.2**, and **5.3** show results applying each chapter's outcomes to the novel framework in this work (**Figure 1.3**). Referring to the tables based on the framework, discussions on the desirable conditions of the energy transition for the society and companies, which were introduced in Section 1.3, are addressed as follows.

Desirable conditions of energy transition (referred from Section 1.3)
For society (Macroscopic);

S-1. A stable balance between supply and demand can be achieved. [Constraint]
S-2. Consistent with the global de-carbonization scenario. [Constraint]
S-3. Affordable economic burden. [Distribution justice]
S-4. Enough equitable energy accessibility. [Distribution justice]

For a company (Microscopic) and companies (Meso-scale);

C-1. Keep sufficient profits or avoid critical losses.
C-2. Acceptable changes in employment and supply chain.
C-3. Well-deserved recognition of efforts to the transition.

First, with regard to society (macroscopic), [S-1] the stable balance between energy supply and demand was given as one of the constraints in Chapter 2 (Section 2.2.3 (1)). Even though energy supply and demand were balanced, the reserve margins became insufficient in the region where capacity of replaced thermal power plants was not enough when large-scale VRE was installed. This implies that the expected capacity shortage should be bridged by power supply from other regions where the reserve margins are greater.

[S-2] The CO_2 restrictions consistent with the Paris agreement were given as another constraint in Chapter 2 (Section 2.2.3 (2)).

[S-3] The scenario in which retiring thermal power plants were replaced and nuclear power plants` lifetimes were extended, was expected to be affordable, but the economic burden of the other scenarios was extremely high under the CO_2 restrictions (Section 2.3.2).

[S-4] Since there is a large difference in the potential for introducing RE by region [110], the large-scale introduction of RE during the energy transition may bring unfairness to the society by region. As Section 2.3.1 (3) and 2.3.6 showed, hydrogen as energy storage with inter-regional transportation could be one of the optimal options of the energy transition, although the media of energy storage and transportation does not necessarily have to be hydrogen. Suppose the region with rich RE sources helps the other region with insufficient RE by energy storage with inter-regional transportation. In that case, the uneven distribution of RE potentials could be mitigated. Besides, the potentials of existing infrastructures are very different by region. The difference could cause the inequity of reserve margins by region, and power supplementation from other regions would be important. Therefore, the inter-regional cooperation based on energy storage with inter-regional transportation and efficient use of existing infrastructures could balance uneven distribution of energy resources during the energy transition.

Second, as for a company (Microscale) and companies (Meso-scale), [C-1] since companies are profitable organizations, they should keep sufficient profits or avoid critical losses during the energy transition. As examined in Chapter 3, there are two conditions that encourage companies to invest in RE, considering gains and losses of investments from non-normative perspectives. One is (a) to reduce the uncertainty of RE investments, and the other is (b) to emphasize that RE investments avoid risks of future loss of company's operation (Section 3.3).

With regard to (a), as Section 3.3.3 showed, balanced investments in both PV and wind yielded a larger VRE capacity. However, it should be difficult for a RE company to introduce both PV and wind power in a balanced manner inside a small area, in reality, considering the unfairness of RE potential by region. That is, the RE company needs to take risks of uncertainty such as variation of capacity factor caused by weather. Therefore, if RE companies in different regions cooperate with each other to compensate for the risk of variation of capacity factor, the uncertainty of investments in RE will be reduced, and RE investment could proceed. Besides, previous literature claims that people could be altruistic for environmental issues under certain conditions [145,146]. The cooperation of RE companies in different regions also may encourage reciprocal altruistic behavior [147], and support future RE investments, although further investigations are needed if the behaviors are applicable to RE investments.

Regarding (b), as Section 3.3 clarified, the co-worker's suggestions that emphasize the risk of not investing in RE lowers the decision-makers' RFP and encourages VRE investments; this is an effect of negative framing [46,47]. This study took the co-worker's suggestions as an example of a behavioral influence factor to the decision-maker, but there should be other factors that shift the decision-maker's RFP lower, as shown in **Figure 3.1**. RE investors may proceed to further RE investments from the future-oriented behavioral decision perspective if the government or conventional utility companies clearly shows replacing and abolishing strategies of existing infrastructure, illuminate issues of energy in the future, emphasize the risk not to invest in RE such as shortage of power, reduction of income and employment of business. However, as Section 4.3.1 showed that companies proactive in energy transition had normal or slightly below financial performance, the energy transition has not seemed profitable for companies in Japan so far. In order to accelerate the energy transition of companies, the government needs to provide appropriate supports until the energy transition goes ahead autonomously, in addition to giving negative framing to companies.

[C-2] Though this study did not discuss changes in employment and the supply chain during the energy transition, it is expected that the efficient use of existing infrastructure could overcome the inertia of society and promote RE investments from employment and supply chain points of view. Since skills and knowledge of RE operation are very different from those of conventional power plants [148,149], employees need to be re-educated and/or to be newly hired. Besides, locations of RE differ from those of conventional power plants, and labor should be relocated and/or newly employed. In addition, because conventional power business has established vertically integrated supply chains, the energy transition should significantly impact the supply chains. Although the energy transition to RE should bring new employment and supply chains, the current employment and supply chains should be gradually changed with the efficient use of existing infrastructures considering the inertia of the society.

[C-3] Company's efforts to the energy transition should be well recognized from a recognition justice point of view. As Section 4.3.2, companies proactive in the energy transition are more aware of their brand in their management policy, although further investigations are needed on the correlativeness between the management policy and the energy transition of the companies. In recent years, companies' efforts for the energy transition have become more socially recognized, such as ESG investments. Moreover, the cooperation of RE companies in different regions could contribute to local society across a broad area, and investments in RE may lead to the company's brand improvement.

Figure 5.1 shows the expected processes to encourage the company's energy transition based on the discussions above. The effective use of existing infrastructure will be a realistic approach to the large-scale RE introduction from a society point of view. Besides, inter-regional cooperation of RE companies in different regions and negative framing of RE investments from the society will encourage the companies' energy transition. It is also important to overview the outcomes of companies' energy transition from financial performance, CO_2 emissions, and management policy aspects in order to observe the influence of past and ongoing company efforts. These processes could make a positive cycle of RE introduction, and this work concludes that inter-regional energy production and cooperation for inter-regional consumption based on the effective replacement of retiring power generation facilities will move companies forward to the energy transition.

Table 5.1 Results of macroscopic perspective applied to the framework of energy transition (future oriented)

Domain	Regions	Perspective
		Macroscopic [Chapter 2]
Power Supply System	Kansai / Chugoku, Shikoku, and Kyushu	**Existing Infrastructure** Chronological replacement of thermal power plant to GTCC saves on costs and electricity surplus and costs for large-scale RE introduction. [Section 2.3.1, 2.3.2] **Technological** **PV**: To be introduced more where the capacity of natural gas-fired power plants is large in the 2040s [Section 2.3.1 (3)] **Wind**: To be introduced more where the capacity of natural gas-fired power plants is small in the 2040s [Section 2.3.1 (3)] **GTCC**: Capacity factor will be less than 20% in the 2040s. To be maintained in regions with insufficient RE potential, unnecessary in regions with enough RE potential in the 2050s. [Section 2.3.4, 2.3.6] **Nuclear**: Effective to meet CO_2 restriction in the 2020s; otherwise, unrealistic secondary batteries are needed [Section 2.3.1. (1)] **Secondary batteries**: Need more capacity with the increasing RE introduction, especially in case of without replacement of thermal power plants. [Section 2.3] **Hydrogen**: Reduces total cost by producing hydrogen with the surplus electricity in regions where many RE are introduced and transferring the hydrogen to regions where the GTCC capacity is relatively larger in the 2040s and 2050s. [Section 2.3.1 (3), 2.3.6] **Reserve ratio**: Continuously to be negative in regions where the replaced thermal power plants are small. [Section 2.3.5] **Environmental: CO_2 restrictions** Given the consistency with the energy mix by the Japanese government [Section 2.2.3 (2)] **Economic** Energy transition to RE with replacing retiring thermal power plants and extending nuclear power plants is feasible. [Section 2.3.2]

Table 5.2 Results of microscopic perspective applied to the framework of energy transition (future oriented)

Domain	Regions	Perspective
		Microscopic [Chapter 3]
RE Company	Kansai	**Existing Infrastructure** The scenario with the replacement of retiring thermal power plants and life extension of nuclear power plants is better from RE company's income and CO_2 emission point of view. (Consistent with the macroscopic perspective) [Section 3.3.2] **Technologies** Preferable RE technologies and capacities are different between normative approach "without" and "with" non-normative. [Section 3.3] **Environmental: CO_2 emissions** CO_2 restrictions encourage RE introduction due to higher spot price in the case of sufficient financial support. [Section 3.3.5]
		Psychological Perspectives **Non-normative decision on top of normative perspective** Heavy investments in either PV or wind results in decreased VRE capacity despite sufficient financial support. [Section 3.3] Balanced investments in both PV and wind yield a larger VRE capacity in cases of sufficient financial support. [Section 3.3.3] Co-worker's suggestions that lowered the decision-makers' RFP encourages VRE investments despite insufficient financial support. [Section 3.3]

Table 5.3 Results of meso-scale perspective applied to the framework of energy transition (past and ongoing)

Domain	Regions	Perspective
		Meso-scale [Chapter 4]
Companies	Japan	**Financial** Financial performance of companies proactive in the energy transition is normal or slightly below. Companies with high financial performance and energy-intensive companies can be relatively less proactive in the energy transition. [Section 4.3.1] **Environmental: CO_2 emissions** Companies proactive in energy transition have larger indirect CO_2 emissions than direct ones and less CO_2 emissions for the company scale. [Section 4.3.1] **Psychological Perspectives** **Management Policy** Companies proactive in energy transition are more aware of their "own brand" and "business strategy" than the other companies. [Section 4.3.2]

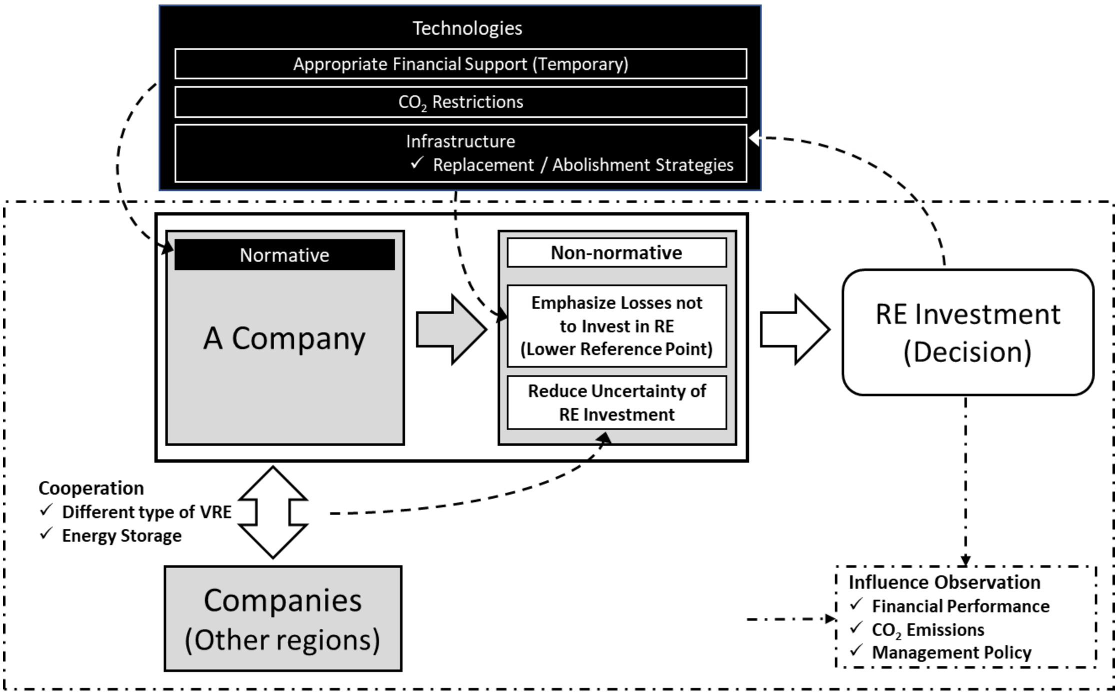


Figure 5.1 Expected process to encourage the company's energy transition based on the results of this work.

5.2 Future Work

This work attempted to examine the energy transition of companies with a new approach from multiple perspectives. Since this work applied quantitative approaches to macroscopic, mesoscale, and microscopic perspectives in order to obtain clear outcomes from each study, there was some abstraction and simplification of real society and technologies in the models. The following conditions are worth noting. Future work should be expected to address the conditions based on the results of this work to obtain future generic suggestions on the energy transition of companies.

- The scope of analysis was limited within companies related to electricity and RE investments. The scope of the study should be expanded to transportation, the home sector, and other industries.
- Although this work focused on power generation facilities as existing infrastructure, there is other energy infrastructure such as the electric transmission system, oil and natural gas storage system, and city gas distribution system. Effective use of this existing infrastructure should be examined as well.
- The energy demand was fixed from a macroscopic perspective since this work focused on energy transition of the supply-side. Energy-saving should be one of the key factors of the energy transition, in reality, changes in energy demand needed to be examined and incorporated.
- Though technologies of energy storage were introduced in the macroscopic analysis, but not in the microscopic analysis due to the difficulty of evaluating the kW and kWh values of energy storage in the energy market. Given the timeframe of microscopic analysis, this assumption was appropriate in this study. However, studies on the value of energy storage should be addressed, and the technologies of energy storage should be considered in the macroscopic analysis in the future.
- From a microscopic perspective, the RE company in the energy market of the region in this work was consolidated into one RE company even though each RE company in the region may interact, in reality. Besides, only two types of the decision maker’s RFP were defined for the simplicity of the model despite while there should be several factors influencing the RFP of the decision-maker. That is, the behavior of each RE company, in reality, could be more complex, and the complexity should be considered.

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Appendix A. Supplement of Chapter 2

A.1 Formulation of the model

A.1.1 Definition of the symbol

In each symbol, uppercase letters indicate exogenous and fixed values, lowercase letters indicate endogenous variables, the subscript i is the district (Kansai: i=1, Chugoku, Shikoku, Kyushu: i=2), j is the technology of interest (see **Figure 2.1** for the numbers of each technology), and t is the time.

A.1.2 Objective function

With the assumptions and constraints set in the text, the total annual cost of the two regions, defined by the following equation, was minimized as an objective function for each period of analysis.

$$\begin{aligned} \min tc = \sum_{i=1}^{2}\sum_{j=1}^{17} \Big\{ & CRF_j \times CC_j \times (cpn_{ij} + CPI_{ij}) \\ & + COM_j \times (CC_j \times cpt_{ij}) + FC_j \times \sum_{t=1}^{8760} mf_{ijt} \Big\} \end{aligned} \tag{A.1}$$

$$cpt_{ij} = cpn_{ij} + CPE_{ij} \tag{A.2}$$

$$CRF_j = \frac{DR}{1-(1+DR)^{-PP_j}} \tag{A.3}$$

where tc is the total cost [=3%], CRF_j is the capital payback factor, DR is the discount rate (=3%), PP_j is the payback period of each technology [years], CC_j is the construction cost of each technology [¥/kW or ¥/kWh], cp_{tij} is the total installed capacity [kW or kWh], CPE_{ij} is the existing installed capacity [kW or kWh], cpn_{ij} is Renewed and new capacity [kW or kWh], CPI_{ij} is the unrecovered capacity from the previous period [kW or kWh], COM_j is the annual operation and maintenance cost ratio to construction cost [%/year], FC_j is the fuel cost [¥/t], and mf_{ijt} is the fuel flow rate [t/h].

A.1.3 Restrictions

(1) Supply-demand balance and interregional interconnection

In the Kansai region, and the Chugoku, Shikoku, and Kyushu regions, the constraint is that the supply and demand are equal and balanced in quantity.

$$op_{ijt} \times \left(1 - \frac{AP_j}{100}\right) \times \left(1 - \frac{TL_j}{100}\right) + ic_{it} = DM_{it} + cs_{ijt} + sp_{it} \tag{A.4}$$

$$ic_{1t} = ic_{21t} - ic_{12t} \tag{A.5}$$

$$ic_{2t} = ic_{12t} - ic_{21t} \tag{A.6}$$

where op_{ijt} is the output of each technology [kWh], AP_j is the internal rate [%], TL_i is the transmission loss [%], icit is the interregional interconnection power [kWh], DM_{it} is the power demand [kWh], cs_{ijt} is the power consumption of each energy storage technology [kWh], and sp_{it} is the power suppression [kWh]. The transmission loss TL_j is assumed to be uniformly 3% for all but PV, and is assumed to be 1% of the average of 0% for households and 3% for mega-solar.

(2) CO_2 emissions

CO_2 emission factors CDL_i [kg-CO_2/kWh] are defined as follows

$$CDL_i \geq \sum_{t=1}^{8760} \sum_{j=1}^{5} \frac{cde_{ijt}}{(op_{ijt} - ic_{it})} \tag{A.7}$$

where cde_{ijt} is the amount of CO_2 emissions [kg/h] for each technology.

(3) Energy storage

Storage batteries are often characterized to have a fixed ratio of maximum power output (MWh) to installed capacity (MWh) (MMW/MWh ratio, ROC_j) [150]. Since this characteristic is also applicable to the lithium-ion batteries studied, the following restriction was incorporated.

$$cpt_{ij} \times ROC_j \geq op_{ijt} \tag{A.8}$$

In addition, the depth of discharge and the self-discharge rate per unit of time were considered for the storage battery.

A.1.4 Reserve ratio

In Section 2.3.5, the reserve factor was defined as follows;

$$rm_{it} = \left(\frac{cpt_{ij} + L5_{ijt}}{DM_{it}} - 1 \right) \times 100 \tag{A.9}$$

where rm_{it} is the reserve ratio [%], cpt_{ij} is the total installed capacity [kW] (j=1-9 for the target technology), and $L5_{ijt}$ is the kW value of the VRE evaluated by the L5 method [kW] (j=10-12 for the target technology).

Based on this definition, the reserve ratio at each time was calculated, and **Figure 2.18** shows the reserve factor at the time with the lowest reserve ratio on each calendar day plotted as the representative point.

A.2 Facility properties

The properties of power generation and storage facilities are set up as follows, and the properties are used in the model as inputs in Chapter 2.

A.2.1 Power generating facilities

Table A.1 shows the properties of power generating facilities.

Table A.1. Properties of power generating facilites

Item	Unit	Technology	Year					Remarks
			2017	2020	2030	2040	2050	
Construction cost (*1)	[yen/kW]	GTCC	NA	120,000 (*5)	120,000 (*5)	120,000 (*5)	120,000 (*5)	[92]
		PV	NA (*4)	273,500	240,000	195,500	195,500	[92] (*2)
		Onshore-wind	NA (*4)	287,000	266,000	245,000	237,000	[92,151]
		Offshore-wind	NA	565,000	496,000	423,000	402,000	[92,151]
		Geothermal	NA	790,000	790,000	790,000	790,000	[92]
		Biomass	NA	410,300	410,300	410,300	410,300	[92]
Operation & Maintenance Cost	[%/year]	GTCC	3.0	3.0 (*5)	3.0 (*5)	3.0 (*5)	3.0 (*5)	[92]
		Oil-fired Steam Power	3.2	3.2	3.2	3.2	3.2	[92]
		Coal-fired Steam Power	4.0	4.0	4.0	4.0	4.0	[92]
		NG-fired Steam Power	3.2	3.2	3.2	3.2	3.2	(*7)
		Other fuel-fired Steam Power	3.2	3.2	3.2	3.2	3.2	(*7)
		Nuclear	5.2	5.2	5.2	5.2	5.2	[92]
		PV	1.2	1.2	1.2	1.2	1.2	[92] (*2)
		Onshore-wind	2.1	2.1	2.1	2.1	2.1	[92]

		Offshore-wind	4.4	4.4	4.4	4.4	4.4	[92]
		General Hydro	1.4	1.4	1.4	1.4	1.4	[92]
		Geothermal	4.2	4.2	4.2	4.2	4.2	[92]
		Biomass	6.8	6.8	6.8	6.8	6.8	[92]
Electrical Efficiency (LHV basis)	[%-LHV]	GTCC (below 1350 deg. C)	55.4	55.4	55.4	55.4	55.4	[92] (*6)
		GTCC (1400-1500 deg. C)	57.6	57.6	57.6	57.6	57.6	[92] (*6)
		GTCC (Cutting-edge)	59.8	59.8	63.1	63.1	63.1	[92] (*6)
		Oil-fired Steam Power	40.0	40	40	40	40	[92] (*3)
		Coal-fired Steam Power	43.5	43.5	43.5	43.5	43.5	[92] (*3)
		NG-fired Steam Power	40.0	40	40	40	40	(*3), (*7)
		Other fuel-fired Steam Power	40.0	40	40	40	40	(*3), (*7)
Auxiliary Power Consumption Rate	[%]	GTCC (*6)	2.0	2	2	2	2	[92]
		Steam Power	6.2	6.2	6.2	6.2	6.2	[92]
Payout Time	[year]	GTCC	15	15	15	15	15	[92]
		PV	10	10	10	10	10	(*8)
		Onshore-wind	10	10	10	10	10	(*8)
		Offshore-wind	10	10	10	10	10	(*8)
		Geothermal	15	15	15	15	15	[92]
		Biomass	15	15	15	15	15	[92]
Lifetime	[year]	GTCC	40	40	40	40	40	[92]
		PV	20	20	20	20	20	[92]
		Onshore-wind	20	20	20	20	20	[92]
		Offshore-wind	20	20	20	20	20	[92]
		Geothermal	40	40	40	40	40	[92]
		Biomass	40	40	40	40	40	[92]
CO_2 Emission Coefficient	[t-CO_2/t]	Oil-fired Steam Power	3.4	3.4	3.4	3.4	3.4	[152]
		Coal-fired Steam Power	2.3	2.3	2.3	2.3	2.3	[152]
		NG-fired Steam Power	2.7	2.7	2.7	2.7	2.7	[152]
		Other fuel-fired Steam Power	0.3	0.3	0.3	0.3	0.3	[152]

Notes

(*1) Cost for abolishing facilities is not considered.

(*2) The average of residential and mega solar since the potential installed capacities of residential and mega solar in western Japan are equivalent.

(*3) The electrical efficiency changes depending on the load factor in reality. However, the constant electrical efficiency is used for simplicity since the electrical utility company operates the units of thermal power generation facilities in the region to maintain as high efficiency as possible.

(*4) Construction cost is not included since the investment has been addressed in FY 2017. The capacity of facilities as of FY 2017 is estimated by the capacity factor and total annual power generation in FY 2017 in public; Capacity of facilities = Total annual power generation / (8760 hours * Capacity factor), where the capacity factor of PV and on-shore wind are expected to be 14% and 20%, respectively.

(*5) When the gas turbine is used for hydrogen-fired, it is assumed that only the combustors of the gas turbine will be replaced and the cost of replacement will be covered by the O&M cost.

(*6) Efficiency and auxiliary power consumption rate of hydrogen-fired are assumed to be the same as that of natural gas-fired.

(*7) Since the information of NG-fired and other gas-fired steam power is not available, data of oil-fired is applied.

(*8) Expected to be half of the lifetime.

A.2.2 Energy Storage

Table A.2 shows the properties of energy storage facilities.

Table A.2. Properties of energy storage facilities

Item	Unit	Technology	Year					Remarks
			2017	2020	2030	2040	2050	
Construction cost (*1)	[yen/kW]	Secondary battery	NA (*9)	90,400	43,500	27,900	12,500	[150] (*11)
		H_2 generation (Alkaline water electrolysis)	NA (*9)	126,500	95,700	86,400	77,000	[153]
		H_2 liquefaction (*10)	NA (*9)	159,500	120,700	109,000	97,100	[153]
		Liquefied H_2 storage	NA (*9)	1,100	900	800	700	[153]
Operation & Maintenance Cost	[%/year]	Secondary battery	NA (*9)	2.0	2.0	2.0	2.0	(*11), (*12)
		PHS	NA (*9)	1.4	1.4	1.4	1.4	[92]
		H_2 generation (Alkaline water electrolysis)	NA (*9)	5	5	5	5	[153]
		H_2 liquefaction (*10)	NA (*9)	2	2	2	2	(*12)
		Liquefied H_2 storage	NA (*9)	2	2	2	2	(*12)
Efficiency	[%]	Secondary battery	NA (*9)	85.3	87.1	87.1	87.1	[150] (*11), (*14)
		PHS	Recorded value	50	50	50	50	[154]
		H_2 generation (Alkaline water electrolysis)	NA (*9)	74.0	75.0	76.5	78.0	[153]
		Liquefied H_2 storage	NA (*9)	70	70	70	70	[153]
Self discharge rate	[%/day]	Secondary battery	NA (*9)	0.36	0.36	0.36	0.36	[150] (*11)
Self energy loss	[%/day]	H_2 liquefaction (*10)	NA (*9)	0	0	0	0	[153] (*13)
Depth of discharge	[%]	Secondary battery	NA (*9)	84.0	84.00	91.25	100.00	[150]

Output / Capacity ratio	[MW/MWh]	Secondary battery	NA (*9)	0.5	0.5	0.5	0.5	[150] (*11)
Payout Time	[year]	Secondary battery	NA (*9)	10	10	10	10	(*11), (*12)
		H_2 generation (Alkaline water electrolysis)	NA (*9)	10	10	10	10	(*12)
		H_2 liquefaction (*10)	NA (*9)	10	10	10	10	(*12)
		Liquefied H_2 storage	NA (*9)	10	10	10	10	(*12)
Lifetime	[year]	Secondary battery	NA (*9)	10	19	19	31	[150] (*11)
		H_2 generation (Alkaline water electrolysis)	NA (*9)	10	10	10	10	[153]
		H_2 liquefaction (*10)	NA (*9)	30	30	30	30	[153]
		Liquefied H_2 storage	NA (*9)	20	20	20	20	[153]

Notes

(*1) – (*8) the same notes in Section A.2.1.

(*9) No new construction is expected.

(*10) It is assumed that the cost of hydrogen transportation between regions is included. However, the cost caused by the difference in transportation distance between each region is regarded as negligible.

(*11) Regarded as Li-ion battery

(*12) Assumed value

(*13) Liquefied hydrogen has a Boil-off of 0.3% / day. However, since the boil-off hydrogen is available as fuel and is not lost, the self-energy loss is set to 0% / day.

(*14) The power converter efficiency of 95% is considered in addition to the battery efficiency when power is charged and discharged in the simulation.

A.3 Sample script

A sample script for the calculation of Chapter 2 is shown as follows. Some minor parts of the script are abbreviated.

```
Set
        t 'time (Month of 5, 7, 8, 10, 12, 1 and 3)' / t0*t743 /

* ### Thermal Power Plant ###
        gt 'Type of GTCC' / GT1, GT2, GT3 /
        btg 'Type of BTG : BTG1 = Oil, BTG2 = Coal, BTG3 = Gas, BTG4 = BFG' / BTG1, BTG2, BTG3, BTG4 /

* ### Variable Renewable ###
        vre 'Type of VRE ; VRE1 = PV, VRE2 = On-shore Wind, VRE3 = Off-shore Wind'
           / VRE1, VRE2, VRE3 /

* ### Energy Storage ###
        es 'Type of Energy Storage, ES1:Battery, ES2:Flywheel' / ES1, ES2 /
```

```
        phs 'PHS' / PHS1 /

* ### H2 System ###
        hts 'Type of H2 Transportation and Storage (HTS)' / HTS1*HTS2 /
*               HTS1: Intermediately Pressurized (Pipeline)
*               HTS2: Liquefied, HTS3: Highly Pressurized,
*               HTS4: Converted to Ammonia, HTS5: Converted to MCH
*               HTS6: Methanation

* ### Interconnection ###
        ic 'Interconnection'
                / ic12, ic21 /

* ### For input ###
        inp 'Elements for Input Data' / TIME, DEM, NUC, HYD, GEO, BIO, PV, WIND-ON, WIND-OFF, PHS, PHS-D, PHS-C /
        top 'Type of Power Plant' / NUC, HYD, GEO, BIO /

* Abbreviation(Number) of Areas
* KS(1) : Kansai, WEST(2) : Other Western Japan (Shikoku, Chugoku and Kyushu)
;

* ### Parameters for Calculations ###
* === Matrix Conversion ===
Parameter
        MC(t) 'Matrix Conversion' /t0 1/
;
        MC(t) = 1;

Display MC;

* === Load Input Data ===
* << Kansai Area >>
$setglobal excel_nam input01_201708
$setglobal excel_dat INPUT_1
$setglobal excel_reg KS!A1:K8761
Parameter INPUT_1(t,inp);
$include   read02_xls

Parameter
        DEM_1(t) 'Demand [MW]'
        VRETR_1(vre,t) 'VRE Output Trend [-]'
        OPP_1(top,t) 'Other Power Plant (Other than Thermal Power)[MW]'
;

        DEM_1(t) = INPUT_1(t, "DEM");

        VRETR_1("VRE1", t) = INPUT_1(t, "PV");
        VRETR_1("VRE2", t) = INPUT_1(t, "WIND-ON");
        VRETR_1("VRE3", t) = INPUT_1(t, "WIND-OFF");

        OPP_1("NUC", t) = INPUT_1(t, "NUC");
        OPP_1("HYD", t) = INPUT_1(t, "HYD");
        OPP_1("GEO", t) = INPUT_1(t, "GEO");
        OPP_1("BIO", t) = INPUT_1(t, "BIO");

Display DEM_1, VRETR_1, OPP_1;

* << Other Western Japan >>
* ! Abbreviated for the appendix. The same codes as “Kansai Area.”

* === Interconnecting Capacity ===
* 2017/Apr. DC Interconnecting Capacity to be the half of capacity
Scalar
INTCP_12 'Interconnecting Capacity from KS to West [MW]' / 2780 /
INTCP_21 'Interconnecting Capacity from West to KS [MW]' / 3900 /
;

* ### Common Parameters ###
* === Gas Specification ===
Scalar
        LHVH 'LHV of H2 [kJ/kg]' / 119754.7 /
        HHVH 'HHV of H2 [kJ/kg]' / 142101.2 /
        ROHH 'Density of H2 [kg/Nm3]' / 0.089938 /
* As per JIS K 2301-2011, 10777 kJ/Nm3-LHV, 12788 kJ/Nm3-HHV
```

```
        LHVA 'LHV of Ammonia [kJ/kg]' / 18552.6 /
        HHVA 'HHV of Ammonia [kJ/kg]' / 22368.4 /
        ROHA 'Density of Ammonia [kg/Nm3]' / 0.76 /
* As per 141000 kJ/Nm3-LHV, 17000 kJ/Nm3-HHV
        LHVG 'LHV of LNG [kJ/kg]' / 49300 /
        HHVG 'HHV of LNG [kJ/kg]' / 54600 /
        ROHG 'Density of Natural Gas [kg/Nm3]' / 0.74 /
;

* === Economics ===
Scalar
        LNGP 'LNG Price [$/mmbtu]' / 10.5 /
* 1 mmbtu = 1,054 MJ

        YPD 'Yen per Dollar [\/$]' / 110 /

        DR 'Discount Rate [-]' / 0.03 /
;

* ### Parameters for Thermal Power Plant ###
* === Load Fixed Capacity ===
* ! Abbreviated for the appendix.

* << Common >>
* === Gross Plant Efficiency ===
Parameter
        EFFG(gt) 'Gross Efficiency of GTCC at 100% Load [%-LHV]'
                / GT1 55.4, GT2 57.6, GT3 63.1 /
        EFFB(btg) 'Gross Efficiency of BTG at 100% Load [%-LHV]'
                / BTG1 40.0, BTG2 43.5, BTG3 40.0, BTG4 40.0 /
;

* === Constants ===
Scalar
        APRG 'Auxiliary Power Rate of GTCC [%]' / 2.0 /
        APRB 'Auxiliary Power Rater of BTG [%]' / 6.2 /
        TLRTP 'Transmission Loss Rate [%]' / 3.0 /
        MXRG 'Max Ramp Rate of GTCC [%/min]' / 5.0 /
        MXRB 'Max Ramp Rate of BTG [%/min]' / 3.0 /
        CDEG 'Carbon Dioxide Emission by Natural Gas per ton [t-CO2/t]' / 2.7 /
;

* === Cost & Fuel ===
Parameter
        CCG(gt) 'Construction Cost of GTCC [\/kW]' / GT1 120000, GT2 120000, GT3 120000 /
        CCB(btg) 'Construction Cost of BTG [\/kW]' / BTG1 200000, BTG2 250000, BTG3 200000, BTG4 200000 /
        OMG(gt) 'Operation & Maintenance Cost of GTCC [%/year]' / GT1 3.0, GT2 3.0, GT3 3.0 /
        OMB(btg) 'Operation & Maintenance Cost of BTG [%/year]' / BTG1 3.2, BTG2 4.0, BTG3 3.2, BTG4 3.2 /
        LHVB(btg) 'LHV of Oil and Coal [kJ/kg]' / BTG1 40200, BTG2 24800, BTG3 49300, BTG4 2520 /
        HHVB(btg) 'HHV of Oil and Coal [kJ/kg]' / BTG1 41200, BTG2 25700, BTG3 54600, BTG4 2640 /
        FLCB(btg) 'Fuel Cost of BTG [$/t]' / BTG1 696.3, BTG2 85.0, BTG3 543.9, BTG4 0.0 /

* Fuel Cost of BTG3 = 11.6 [$/mmbtu] / 1054[MJ/mmbtu] x 49300[kJ/kg]

        CDEB(btg) 'Carbon Dioxide Emission by Ohter Fuel per ton [t-CO2/t]' / BTG1 3.53, BTG2 2.33, BTG3 2.7, BTG4 0.266 /
* Oil 3.00 t-CO2/kl, 1bbl = 0.135t = 0.159 kl ->
* BFG 0.33 t-CO2/1000Nm3, 1.24 kg/Nm3 -> 0.266 t-CO2/t
* COG 0.85 t-CO2/1000Nm3, 0.43 kg/Nm2 -> 1.976 t-CO2/t
;

* === Payback Period ===
Parameter
        PBPG(gt) 'Payback period of GTCC [Year]' / GT1 15, GT2 15, GT3 15 /
        PBPB(btg) 'Payback period of BTG [Year]' / BTG1 15, BTG2 15, BTG3 15, BTG4 15 /
;

* === Correction Factor of GTCC Capacity for Ambient Temperature ===
* ! Abbreviated for the appendix.

* ### Parameters for VRE ###
* << Kansai Area >>
* === Capacity Limitation ===
Parameter
        CLVRE_1(vre) 'Capacity Limitation of VRE [MW]' / VRE1 39310, VRE2 11570, VRE3 30220 /
```

```
        SFLVRE_1(vre) 'Scale Factor Limitation of VRE [-]' / VRE1 9.5, VRE2 91.1, VRE3 158.6 /
        CBVRE_1(vre) 'Base Capacity of VRE for scale calculation [MW]' / VRE1 4153, VRE2 147, VRE3 147 /
;

* === Existing Capacity ===
Parameter
        CEVRE_1(vre) 'Existing Capacity of VRE [MW]' / VRE1 4153, VRE2 147.0, VRE3 0.0 /
;

* << Other Western Japan >>
* === Capacity Limitation ===
* ! Abbreviated for the appendix. The same codes as “Kansai Area.”
;

* << Common >>
* === Cost ===
Parameter
        CCVRE(vre) 'Construction Cost of VRE [\/kW]' / VRE1 240000, VRE2 266000, VRE3 496000 /
        OMVRE(vre) 'Operation and Maintenance Cost of VRE [%/year]' / VRE1 1.2, VRE2 2.1, VRE3 4.4 /
;

* === Transmission Loss ===
Parameter
        TLRVRE(vre) 'Transmission Loss Rate of VRE [%]' / VRE1 1.5, VRE2 3.0, VRE3 3.0 /
;

* === Payback Period ===
Parameter
        PBPVRE(vre) 'Payback period of VRE [Year]' / VRE1 10, VRE2 10, VRE3 10 /
;

* ### Parameters for Energy Storage ###
* << Kansai Area >>
Parameter
        CPPHS_1(phs) 'Capacity of PHS [MWh]' / PHS1 24000 /
        MXOPHS_1(phs) 'Max Output of PHS [MW]' / PHS1 3000 /
        CLES_1(es) 'Capacity Limitation (Potential Capacity) of ES [MWh]' / ES1 10000000000, ES2 10000000000 /
;

* === Existing Capacity ===
Parameter
        CEES_1(es) 'Existing Capacity of ES [MWh]' / ES1 0.0, ES2 0.0 /
* To be set in line with the results of previous phase
;

* << Other Western Japan >>
* ! Abbreviated for the appendix. The same codes as “Kansai Area.”

* << Common >>
* === Cost ===
Parameter
        CCES(es) 'Construction Cost of ES [\/kWh]' / ES1 43500, ES2 430900 /
        CCPHS(phs) 'Construction Cost of PHS [/kWh\]' / PHS1 47000 /
        OMES(es) 'Operation & Maintenance Cost of ES to the Const. Cost [%/year]' / ES1 2.0, ES2 2.0 /
        OMPHS(phs) 'Operation & Maintenance Cost of PHS to the Const. Cost [%/year]' / PHS1 1.4 /
;

* === Efficiency & Self-discharge Rate ===
Parameter
        EFFES(es) 'Efficiency of ES [%]' / ES1 87.1, ES2 87.0 /
        EFFPHS(phs) 'Efficiency of PHS [%]' / PHS1 50.0 /
        SDES(es) 'Self-discharge Rate of ES [%/day]' / ES1 0.36, ES2 42.61 /
;

* === Limitation for Ratio of Output to Capacity ===
Parameter
        ROCES(es) 'To be less than the following values for ES [MW/MWh]' / ES1 0.5, ES2 4.0 /
        ROCPHS(phs) 'To be less than the following value for PHS [MW/MWh]' / PHS1 0.1 /
;

* === Depth of Discharge ===
Parameter
        DOD(es) 'Depth of discharge [%]' / ES1 84, ES2 75 /
;
```

```
* === Payback Period ===
Parameter
        PBPES(es) 'Payback period of ES [Year]' / ES1 10, ES2 10 /
;

* ### Parameters for H2 System ###
* << Kansai Area >>
* === Capacity Limitation ===
Parameter
        CLHG_1(hts) 'Capacity Limitation of H2 Generation [MWh]' / HTS1 1000000000, HTS2 1000000000 /
        CLHT_1(hts) 'Capacity Limitation of H2 Transportation [MWh]' / HTS1 1000000000, HTS2 1000000000 /
        CLHS_1(hts) 'Capacity Limitation of H2 Storage [MWh]' / HTS1 1000000000, HTS2 1000000000 /
;

* === Existing Capacity ===
Parameter
        CEHG_1(hts) 'Existing Capacity of H2 Generation [MWh]' / HTS1 0.0, HTS2 0.0 /
        CEHT_1(hts) 'Existing Capacity of H2 Transportation [MWh]' / HTS1 0.0, HTS2 0.0 /
        CEHS_1(hts) 'Existing Capacity of H2 Storage [MWh]' / HTS1 0.0, HTS2 0.0 /

* To be set in line with the results of previous phase
;

* << Other Western Japan >>
* === Capacity Limitation ===
* ! Abbreviated for the appendix. The same codes as “Kansai Area.”
;

* << Inter-Area for H2 System >>
* ! Abbreviated for the appendix.
* << Common >>
* === Cost ===
Parameter
        CCHG(hts) 'Construction Cost of H2 Generation [\/kW]' / HTS1 95700, HTS2 95700 /
        CCHT(hts) 'Construction Cost of H2 Transportation [\/kWh]' / HTS1 58300, HTS2 120700 /
        CCHS(hts) 'Construction Cost of H2 Storage [\/kWh]' / HTS1 0.0, HTS2 900 /
* Technology Roadmap Hydrogen and Fuel Cell

        OMHG(hts) 'Operation & Maintenance Cost of H2 Generation to the Construction Cost [%/year]' / HTS1 5.0, HTS2 5.0 /
        OMHT(hts) 'Operation & Maintenance Cost of H2 Transportation to the Construction Cost [%/year]' / HTS1 0.00, HTS2 2.0 /
        OMHS(hts) 'Operation & Maintenance Cost of H2 Storage to the Construction Cost [%/year]' / HTS1 2.0, HTS2 2.0 /
        TCHT(hts) 'Transportation Cost of H2 [\/kWh]' / HTS1 0.000, HTS2 0.000 /
;

* === Payback Period ===
Parameter
        PBPHG(hts) 'Payback period of H2 Generation [Year]' / HTS1 10, HTS2 10 /
        PBPHT(hts) 'Payback period of H2 Transportation [Year]' / HTS1 10, HTS2 10 /
        PBPHS(hts) 'Payback period of H2 Storage [Year]' / HTS1 10, HTS2 10 /
;


* === Efficiency ===
Parameter
        EFFHG(hts) 'Efficiency of H2 Generation [%]' / HTS1 75.0, HTS2 75.0 /
        EFFHT(hts) 'Efficiency of H2 Transportation [%]' / HTS1 95.0, HTS2 70.0 /
        SDHS(hts) 'Self-discharge Rate of H2 Storage [%/day]' / HTS1 0.0, HTS2 0.0 /
;

* === Hydrogen Mixture Limitation ===
Scalar
        HIG 'H2 in Fuel Gas [vol%]' / 100.0 /
        HIP 'H2 in the Exisiting Natural Gas Piping [vol%]' / 30.0 /
;

* ### Parameters for Other Power Plants ###
* << Kansai Area >>
Parameter
        CEOPP_1(top) 'Existing Capacity of Other Power Plant [MW]' / NUC 5260, HYD 3575, GEO 0, BIO 165 /
        CPOPP_1(top) 'Equipment Capacity of Other Power Plant [MW]' / NUC 5260, HYD 3575, GEO 0, BIO 715 /
        CNOPP_1(top) 'Capacity of Non-payback Other Power Plant [MW]' / NUC 0, HYD 0, GEO 0, BIO 83 /
        SFOPP_1(top) 'Scale Factor of Other Power Plant [-]' / NUC 1, HYD 1, GEO 1, BIO 3.7 /
        OPOPP_1(top,t) 'Output of Other Power Plant [MWh]'
```

```
;

Scalar
        CFNUC_1 'Capacity Factor of Nuclear [-]' / 0.8 /
;

        OPP_1("NUC",t) = CPOPP_1("NUC")*CFNUC_1*MC(t);
        OPP_1("BIO",t) = OPP_2("BIO",t);
        OPOPP_1(top,t) = OPP_1(top,t)*SFOPP_1(top)*MC(t);

* << Other Western Japan >>
* ! Abbreviated for the appendix. The same codes as “Kansai Area.”

* << Common >>
Parameter
        CCOPP(top) 'Construction Cost of Other Power Plant [\/kW]' / NUC 370000, HYD 640000, GEO 790000, BIO 410300 /
        OMOPP(top) 'Operation & Maintenance Cost of Other Power Plant [%/year]' / NUC 5.2, HYD 1.4, GEO 4.2, BIO 6.8 /
;

Parameter
        PBPOPP(top) 'Payback period of Other Power Plant [Year]' / NUC 15, HYD 15, GEO 15, BIO 15 /
;

* << Dummy Output for the Balance >> *
* ! Abbreviated for the appendix.

Variable
* ### Variables for Thermal Power Plant ###
* << Kansai Area >>
        opg_1(gt,t) 'Gross Output of GTCC [MW]'
        fcg_1(gt,t) 'Fuel Consumption of GTCC [GJ]'
        fclng_1(t) 'Total LNG Consumption of GTCC [GJ]'
        lrg_1(gt,t) 'Load Rate of GTCC [-]'
        opb_1(btg,t) 'Gross Output of BTG [MW]'
        fcb_1(btg,t) 'Fuel Consumption of BTG [GJ]'
        lrb_1(btg,t) 'Load Rate of BTG [-]'

        tpcost_1 'Thermal Power Plant Cost [M\]'
        flcost_1 'Fuel Cost [M\]'
        cdems_1 'CO2 Emission [t-CO2/t]'
        cdemsh_1(t) 'CO2 Emission [t-CO2/t/h]'
        cdemsk_1 'CO2 Emission per kWh [kg-CO2/kWh]'

* << Other Western Japan >>
* ! Abbreviated for the appendix. The same codes as “Kansai Area.”

* ### Variables for VRE ###
* << Kansai Area >>
        sfvre_1(vre) 'Scale Factor of VRE [-]'
        opvre_1(vre,t) 'Output of VRE [MW]'
        cpvre_1(vre) 'Equipment Capacity of VRE including Existing [MW]'
        vrecost_1 'VRE Cost [M\]'

* << Other Western Japan >>
* ! Abbreviated for the appendix. The same codes as “Kansai Area.”

* ### Variables for Energy Storage ###
* << Kansai Area >>
        cses_1(es,t) 'Power Consumption of ES [MW]'
        dces_1(es,t) 'Power Discharge of ES [MW]'
        stes_1(es,t) 'Power Storage Amount of ES [MWh]'
        cpes_1(es) 'Equipment Capacity of ES [MWh]'
        escost_1 'ES Cost [M\]'

        csphs_1(phs,t) 'Power Consumption of PHS [MWh]'
        dcphs_1(phs,t) 'Power Discharge f PHS [MWh]'
        stphs_1(phs,t) 'Power Storage Amount of PHS [MWh]'

* << Other Western Japan >>
* ! Abbreviated for the appendix. The same codes as “Kansai Area.”

* ### Variables for H2 System ###
* << Kansai Area >>
        cshg_1(hts,t) 'Power Consumption of H2 Generation [MWh]'
```

```
        hgen_1(hts,t) 'H2 Generation Amount as per Energy [MWh]'
        hgvf_1(hts,t) 'H2 Generation Amount as per Volume [Nm3]'
        hgmf_1(hts,t) 'H2 Generation Amount as per Mass [t]'
        cphg_1(hts) 'Equipment Capacity of H2 Generation [MWh]'

        hten_1(hts,t) 'H2 Transportation Amount as per Energy [MWh]'
        htvf_1(hts,t) 'H2 Transportation Amount as per Volume [Nm3]'
        htmf_1(hts,t) 'H2 Transportation Amount as per Mass [t]'
        cpht_1(hts) 'Equipment Capacity of H2 Transportation [MWh]'

        hsen_1(t) 'H2 Storage Amount as per Energy [MWh]'
        hsvf_1(hts,t) 'H2 Storage Amount as per Volume [Nm3]'
        hsmf_1(hts,t) 'H2 Storage Amount as per Mass Flow [t]'
        cphs_1 'Equipment Capacity of H2 Storage [MWh]'

        dchs_1(t) 'Discharge of H2 from the Storage [MWh]'

        hycost_1 'H2 System Cost'

* << Other Western Japan >>
* ! Abbreviated for the appendix. The same codes as “Kansai Area.”

* << Inter-Area >>
        hsen_ia(t) 'H2 Storage Amount as per Energy [MWh]'
        cphs_ia 'Equipment Capacity of H2 Storage [MWh]'

        dchs_ia1(t) 'Discharge of H2 from the Storage to Kansai [MWh]'
        dchs_ia2(t) 'Discharge of H2 from the Storage to Other Western Japan [MWh]'

        hycost_ia 'H2 System Cost'

* ### Variables for Other Power Plant ###
* << Kansai Area >>
        oppcost_1 'Other Power Plant Cost'

* << Other Western Japan >>
* ! Abbreviated for the appendix. The same codes as “Kansai Area.”

* ### Common Variables ###
* << Interconnection >>
* Interconnected Power
        intp_12(t) 'Interconnected Power from KS to West [MW]'
        intp_21(t) 'Interconnected Power from West to KS [MW]'

* << Power Suppression >>
        sup_1(t) 'Power Suppression of Kansai [MW]'
        sup_2(t) 'Power Suppression of West [MW]'

* << Total Area Cost >>
        cost_1 'Total Area Cost of Kansai Area [M\]'
        cost_2 'Total Area Cost of Other Western Japan[M\]'

* << Common >>
        z 'Objective Function'
        tc 'Total Cost [M\]'
        tctp 'Total Thermal Power Plant Cost [M\]'
        tfc 'Total Fuel Cost [M\]'
        tcvre 'Total VRE Cost [M\]'
        tces 'Total ES Cost [M\]'
        tchy 'Total H2 System Cost [M\]'
        tcde 'Total Carbon Dioxide Emission [t-CO2]'
;

Positive Variable
* ! Abbreviated for the appendix.
;

Equation
* << Common >>
        TotalCost 'Total Cost [M\]'
        TotalTPCost 'Total Thermal Power Plant Cost [M\]'
        TotalFuelCost 'Total Fuel Cost [M\]'
        TotalVRECost 'Total VRE Cost Calculation [M\]'
```

```
        TotalESCost 'Total ES Cost Calculation [M\]'
        TotalH2Cost 'Total H2 System Cost Calculation [M\]'
        TotalCO2Emis 'Total CO2 Emission [t-CO2]'

* << Interconnection >>
        IntCap_12(t) 'Interconnecting Capacity from KS to West'
        IntCap_21(t) 'Interconnecting Capacity from West to KS'

* << Kansai Area >>
        AreaCost_1 'Minimum Cost during operation'
        Balance_1(t) 'Balance of Supply and Demand'

* ### Thermal Power Plant ###
        CapGT_1(gt,t) 'Restriction of the Capacity for GTCC'
        FuelGT_1(gt,t) 'Fuel Gas Consumption of GTCC'
        LoadGT_1(gt,t) 'Load Rate of GTCC'
        CapBTG_1(btg,t) 'Restriction of the Capacity for BTG'
        FuelBTG_1(btg,t) 'Fuel Consumption of BTG'
        LoadBTG_1(btg,t) 'Load Rate of BTG'
        TPCostCalc_1 'Thermal Power Plant Cost Calculation [M\]'
        FLCostCalc_1 'Fuel Cost Calculation [M\]'
        CO2Calc_1 'Total CO2 Calculation [t-CO2/t]'
        CO2phCalc_1(t) 'CO2 per hour Calculation [t-CO2/t/h]'
        CO2pkCalc_1 'CO2 per kWh Calculation [kg-CO2/kWh]'

* ### VRE ###
        OutputVRE_1(vre,t) 'Output of VRE [MW]'
        ScaleFactorVRE1_1(vre) 'Scale Factor of VRE [-]'
        ScaleFactorVRE2_1(vre) 'Scale Factor of VRE [-]'
        SFLimitVRE_1(vre) 'Scale Factor Limitation of VRE [-]'
        EqpCapacityVRE_1(vre) 'Equipment Capacity of VRE [MW]'
        CapLimitVRE_1(vre) 'Equipment Capacity Limitation of VRE [MW]'
        CapMinVRE_1(vre) 'Minimum Capacity of VRE [MW]'
        VRECostCalc_1 'VRE Cost Calculation [M\]'

* ### Energy Storage ###
        StorageES_1(es,t) 'Power Storage Amount of ES [MWh]'
        DischargeES_1(es,t) 'Power Discharge of ES [MWh]'
        EqpCapacityES_1(es,t) 'Equipment Capacity of ES [MWh]'
        MXCapacityES_1(es) 'Max Capacity of ES [MWh]'
        ROCLimitationES_1(es,t) 'Limitation for the Ratio of Output to Capacity, ES [MW/MWh]'

        StoragePHS_1(phs,t) 'Power Storage Amount of PHS [MWh]'
        DischargePHS_1(phs,t) 'Equipment Capacity of PHS [MWh]'
        EqpCapacityPHS_1(phs,t) 'Equipment Capacity of PHS [MWh]'
        MXOutputPHS_1(phs,t) 'Max Output of PHS [MW]'
        ROCLimitationPHS_1(phs,t) 'Limitation for the Ratio of Output to Capacity, PHS [MW/MWh]'

        ESCostCalc_1 'ES Cost Calculation [M\]'

* ### H2 System ###
        H2Cost_1 'Cost of H2 Generation, Transportation and Storage [M\]'

        H2Generation_1(hts,t) 'H2 Generation [MWh]'
        EqpCapacityHG_1(hts,t) 'Equipment Capacity of H2 Generation [MWh]'
        MXCapacityHG_1(hts) 'Max Capacity of H2 Generation [MWh]'

        H2CarrierAmmount_1(hts,t) 'H2 Carrier Amount through H2 Transportation [MWh]'
        EqpCapacityHT_1(hts,t) 'Equipment Capacity of H2 Transportation [MWh]'
        MXCapacityHT_1(hts) 'Max Capacity of H2 Transportation [MWh]'

        StorageHS_1(t) 'Power Storage Amount of H2 Storage [MWh]'
        EqpCapacityHS_1(t) 'Equipment Capacity of H2 Storage [MWh]'
        MXCapacityHS_1 'Max Capacity of H2 Storage [MWh]'
        DischargeHS_1(t) 'Discharge from H2 Storage [MWh]'

        H2ConsGT_1(t) 'H2 Consumption of GTCC [MWh]'

        H2MixLimit01_1(t) 'H2 Mixture Limitation to the Total Fuel Consumption [%]'

* ### Other Power Plant ###
        OPPCostCalc_1 'Cost of Other Power Plant [M\]'

* << Other Western Japan >>
```

```
* ! Abbreviated for the appendix. The same codes as “Kansai Area.”

* << Inter-Area for H2 System >>
* ### H2 System ###
        H2Cost_ia 'Cost of H2 Generation, Transportation and Storage [M\]'

        StorageHS_ia(t) 'Power Storage Amount of H2 Storage [MWh]'
        EqpCapacityHS_ia(t) 'Equipment Capacity of H2 Storage [MWh]'
        MXCapacityHS_ia 'Max Capacity of H2 Storage [MWh]'
        DischargeHS_ia(t) 'Discharge from H2 Storage [MWh]'
;

* <><><> EXECUTE CALCULATIONS <><><>
* ### Set First if needed ###
* === To set Minimum Load of Thermal Power Plants ===
Equation
        MinLoadG_1(gt,t) 'Minimum Load of GTCC'
        MinLoadB_1(btg,t) 'Minimum Load of BTG'

        MinLoadG_2(gt,t) 'Minimum Load of GTCC'
        MinLoadB_2(btg,t) 'Minimum Load of BTG'
;

Parameter
        MINLG(gt) 'Minimum Load of GTCC [%]' / GT1 0.0, GT2 0.0, GT3 0.0 /
        MINLB(btg) 'Minimum Load of BTG [%]' / BTG1 0.0, BTG2 0.0, BTG3 0.0, BTG4 0.0 /
;

* === To set when VREs are defined as Exogenous Parameters ===
Equation
        FixedVRE_1(vre) 'VRE scale factor is fixed as Exogenous Parameter
        FixedVRE_2(vre) 'VRE scale factor is fixed as Exogenous Parameter'
;

Parameter
        EXOVRE_1(vre) 'VRE as Exogenous Parameter' / VRE1 1.0, VRE2 1, VRE3 0 /
        EXOVRE_2(vre) 'VRE as Exogenous Parameter' / VRE1 1.5, VRE2 24.9, VRE3 0 /
;
        FixedVRE_1(vre).. sfvre_1(vre) =e= EXOVRE_1(vre);
        FixedVRE_2(vre).. sfvre_2(vre) =e= EXOVRE_2(vre);

* === To set ES and/or H2 System as Exogenous Parameters ===
Equation
        FixedES_1(es) 'ES Capacity is fixed as Exogenous Parameter'
        FixedES_2(es) 'ES Capacity is fixed as Exogenous Parameter'

        FixedHG_1(hts) 'H2 Generation Capacity is fixed as Exogenous Parameter'
        FixedHG_2(hts) 'H2 Generation Capacity is fixed as Exogenous Parameter'

        FixedHT_1(hts) 'H2 Transportation Capacity is fixed as Exogenous Parameter'
        FixedHT_2(hts) 'H2 Transportation is fixed as Exogenous Parameter'

        FixedHS_1 'H2 Storage Capacity is fixed as Exogenous Parameter'
        FixedHS_2 'H2 Storage Capacity is fixed as Exogenous Parameter'
        FixedHS_ia 'H2 Storage Capacity is fixed as Exogenous Parameter'
;

Parameter
        EXOES_1(es) 'ES as Exogenous Paramater' / ES1 30437.0, ES2 0.0 /
        EXOES_2(es) 'ES as Exogenous Paramater' / ES1 43078.0, ES2 0.0 /
        EXOHG_1(hts) 'H2 Generation as Exogenous Paramater' / HTS1 0.0, HTS2 0.0 /
        EXOHG_2(hts) 'H2 Generation as Exogenous Paramater' / HTS1 0.0, HTS2 0.0 /
        EXOHT_1(hts) 'H2 Transportation as Exogenous Paramater' / HTS1 0.0, HTS2 0.0 /
        EXOHT_2(hts) 'H2 Transportation as Exogenous Paramater' / HTS1 0.0, HTS2 0.0 /
;

Scalar
        EXOHS_1 'H2 Storage as Exogenous Paramater' / 0.0 /
        EXOHS_2 'H2 Storage as Exogenous Paramater' / 0.0 /
        EXOHS_ia 'H2 Storage as Exogenous Paramater' / 0.0 /
;

        FixedES_1(es).. cpes_1(es) =e= EXOES_1(es);
        FixedES_2(es).. cpes_2(es) =e= EXOES_2(es);
```

```
            FixedHG_1(hts).. cphg_1(hts) =e= EXOHG_1(hts);
            FixedHG_2(hts).. cphg_2(hts) =e= EXOHG_2(hts);

            FixedHT_1(hts).. cpht_1(hts) =e= EXOHT_1(hts);
            FixedHT_2(hts).. cpht_2(hts) =e= EXOHT_2(hts);

            FixedHS_1.. cphs_1 =e= EXOHS_1;
            FixedHS_2.. cphs_2 =e= EXOHS_2;
            FixedHS_ia.. cphs_ia =e= EXOHS_ia;

* === To set Limitation of CO2 Emission ===
Scalar
            CDLMPK 'Carbon Dioxide Emission Limit per kWh [kg/kWh]' / 0.37/
;

Equation
            CO2EmisLimit_1 'Limitation of CO2 Emission for Kansai [kg/kWh]'
            CO2EmisLimit_2 'Limitation of CO2 Emission for Other Western Japan [kg/kWh]'
;
            CO2EmisLimit_1.. cdems_1 =l= CDLMPK*(sum(t, DEM_1(t)) + sum(t, intp_12(t)) - sum(t, intp_21(t)));
            CO2EmisLimit_2.. cdems_2 =l= CDLMPK*(sum(t, DEM_2(t)) + sum(t, intp_21(t)) - sum(t, intp_12(t)));


* === Set Dummy Output for the calculation conversion if needed ===

            DUM_1("t0") = 0;
            DUM_2("t0") = 0;

* === Set Initial Storages from ex-month calculation ===
Parameter
            INITES_1(es,t) 'Initial Storage of ES [MWh]'
            INITES_2(es,t) 'Initial Storage of ES [MWh]'

            INITPHS_1(phs,t) 'Initial Storage of ES [MWh]'
            INITPHS_2(phs,t) 'Initial Storage of ES [MWh]'

            INITHTS_1(t) 'Initial Storage of H2 [MWh]'
            INITHTS_2(t) 'Initial Storage of H2 [MWh]'
            INITHTS_ia(t) 'Initial Storage of H2 [MWh]'
;

* Initialize the storage
            INITES_1(es,t) = 0;
            INITES_2(es,t) = 0;

            INITPHS_1(phs,t) = 0;
            INITPHS_2(phs,t) = 0;

            INITHTS_1(t) = 0;
            INITHTS_2(t) = 0;
            INITHTS_ia(t) = 0;

* Set the initial storage
            INITES_1("ES1","t0") = 0;
            INITES_1("ES2","t0") = 0;
            INITES_2("ES1","t0") = 0;
            INITES_2("ES2","t0") = 0;

            INITPHS_1("PHS1","t0") = 23990;
            INITPHS_2("PHS1","t0") = 34390;

            INITHTS_1("t0") = 0;
            INITHTS_2("t0") = 0;
            INITHTS_ia("t0") = 0;

* === Set Fixed Storage Capacity ===
Equation
            FixedCapacityES2_1 'Fixed Storage Capacity of ES2'
            FixedCapacityES2_2 'Fixed Storage Capacity of ES2'

            FixedCapacityHTS1_1 'Fixed Storage Capacity of HTS1'
            FixedCapacityHTS1_2 'Fixed Storage Capacity of HTS1'
;
```

```
        FixedCapacityES2_1.. cpes_1("ES2") =e= 0;
        FixedCapacityES2_2.. cpes_2("ES2") =e= 0;

        FixedCapacityHTS1_1.. cphs_1 =e=0;
        FixedCapacityHTS1_2.. cphs_2 =e=0;

* === Objective Function ===
Equation
        MinCost 'Minimum Cost of the System [M\]'
;
        MinCost.. z =e= tc;

* === Constrains ===
* << Kansai Area >>
* Balance of Supply and Demand
        Balance_1(t).. sum(gt, opg_1(gt,t))*(1-APRG/100)*(1-TLRTP/100)
                    + sum(btg, opb_1(btg,t))*(1-APRB/100)*(1-TLRTP/100)
                    + sum(vre, opvre_1(vre,t)*(1-TLRVRE(vre)*MC(t)/100))
                    + sum(top, OPOPP_1(top,t))
                    + sum(es, dces_1(es,t))
                    + sum(phs, dcphs_1(phs,t))
                    - intp_12(t) + intp_21(t)
                    =e= DEM_1(t)
                        + sum(es, cses_1(es,t))
                        + sum(phs, csphs_1(phs,t))
                        + sum(hts, cshg_1(hts,t))
                        + sup_1(t)
                        - DUM_1(t)
;

* ### Thermal Power Plant ###
* Gross Output should be less than the Capacity
        CapGT_1(gt,t).. opg_1(gt,t) =l= CPEG_1(gt)*CATG(t) + CPRG_1(gt)*CATG(t);
        CapBTG_1(btg,t).. opb_1(btg,t) =l= CPEB_1(btg)*MC(t);

* Load should be above the Minimum Load
        MinLoadG_1(gt,t).. lrg_1(gt,t) =g= MINLG(gt)/100*MC(t);
        MinLoadB_1(btg,t).. lrb_1(btg,t) =g= MINLB(btg)/100*MC(t);


* ### VRE ###
* VRE Equipment Capacity should be less than the Limitation
        CapLimitVRE_1(vre).. cpvre_1(vre) =l= CLVRE_1(vre);
        CapMInVRE_1(vre).. cpvre_1(vre) =g= CEVRE_1(vre);

* Scale Factor should be greater than 1.0 but less than the limitation
        ScaleFactorVRE1_1("VRE1").. sfvre_1("VRE1") =g= 1.0;
        ScaleFactorVRE2_1("VRE2").. sfvre_1("VRE2") =g= 1.0;
        SFLimitVRE_1(vre).. sfvre_1(vre) =l= SFLVRE_1(vre);

* ### Energy Storage ###
* Discharge should be less than the Power Storage Amount & Equipment Capacity
        DischargeES_1(es,t).. dces_1(es,t) =l= stes_1(es,t-1);

        DischargePHS_1(phs,t).. dcphs_1(phs,t) =l= stphs_1(phs,t-1);
        MXOutputPHS_1(phs,t).. dcphs_1(phs,t) =l= MXOPHS_1(phs)*MC(t);
        EqpCapacityPHS_1(phs,t).. stphs_1(phs,t) =l= CPPHS_1(phs)*MC(t);

* Ratio of Output to Capacity should be less than the limitations
        ROCLimitationES_1(es,t).. dces_1(es,t) =l= cpes_1(es)*ROCES(es)*MC(t);
        ROCLimitationPHS_1(phs,t).. dcphs_1(phs,t) =l= cpphs_1(phs)*ROCPHS(phs)*MC(t);


* ### H2 System ###
* Discharge should be less than the Power Storage Amount & Equipment Capacity
        DischargeHS_1(t).. dchs_1(t) =l= hsen_1(t);

* Hydrogen Mixture Limitation
       H2MixLimit01_1(t).. (dchs_1(t)+dchs_ia1(t))*3.6/LHVH/ROHH
                    =l= HIG/100 * ((dchs_1(t)+dchs_ia1(t))*3.6/LHVH/ROHH+fclng_1(t)/LHVG/ROHG+0.0001);

* << Other Western Japan >>
* ! Abbreviated for the appendix. The same codes as “Kansai Area.”
```

```
* << Inter-Area for H2 System >>
* Discharge should be less than the Power Storage Amount & Equipment Capacity
         DischargeHS_ia(t).. dchs_ia1(t) + dchs_ia2(t) =l= hsen_ia(t);

* << Common >>
* Interconnected Power should be less than the capacity
         IntCap_12(t).. intp_12(t) =l= INTCP_12*MC(t);
         IntCap_21(t).. intp_21(t) =l= INTCP_21*MC(t);

* === Calculations ===
* << Kansai Area >>
* Area Cost [M\]
         AreaCost_1.. cost_1 =e= tpcost_1/12 + flcost_1 + vrecost_1/12 + escost_1/12   + hycost_1/12 + oppcost_1/12;

* ### Thermal Power Plant ###
* Fuel Consumption Calculation [GJ-LHV]
         FuelGT_1(gt,t).. fcg_1(gt,t) =e= opg_1(gt,t)/(EFFG(gt)/100*MC(t))/1000*3600;
         FuelBTG_1(btg,t).. fcb_1(btg,t) =e= opb_1(btg,t)/(EFFB(btg)/100*MC(t))/1000*3600;

* Plant Load Rate Calculation [-]
         LoadGT_1(gt,t).. lrg_1(gt,t)*((CPEG_1(gt) + CPRG_1(gt))*MC(t)) =e= opg_1(gt,t);
         LoadBTG_1(btg,t).. lrb_1(btg,t)*(CPEB_1(btg)*MC(t)) =e= opb_1(btg,t);

* Thermal Power Plant Cost
         TPCostCalc_1.. tpcost_1 =e= sum(gt, CPRG_1(gt)*1000*CCG(gt)*DR/(1-((1+DR)**(-PBPG(gt)))))/(10**6)
                                     + sum(gt, (CPEG_1(gt) + CPRG_1(gt))*1000*CCG(gt)*(OMG(gt)/100)/(10**6))
                                     + sum(gt, CPNG_1(gt)*1000*CCG(gt)*DR/(1-((1+DR)**(-PBPG(gt)))))/(10**6)
                                     + sum(btg, CPEB_1(btg)*1000*CCB(btg)*(OMB(btg)/100)/(10**6));

* Fuel Cost
         FLCostCalc_1.. flcost_1 =e= sum(t, fclng_1(t)/1.054*LNGP*YPD)/(10**6)
                                + sum((btg,t), fcb_1(btg,t)/(LHVB(btg)*MC(t))*(10**3)*(FLCB(btg)*MC(t))*YPD/(10**6));

* CO2 Calculation
         CO2Calc_1.. cdems_1 =e= sum(t, fclng_1(t)*(10**3)/LHVG*CDEG)
                                 + sum((btg,t), (opb_1(btg,t)*3600/(LHVB(btg)*EFFB(btg)*MC(t))*100)*CDEB(btg)*MC(t));
         CO2phCalc_1(t).. cdemsh_1(t) =e= fclng_1(t)*(10**3)/LHVG*CDEG
                                + sum(btg, (opb_1(btg,t)*3600/(LHVB(btg)*EFFB(btg)*MC(t))*100)*CDEB(btg)*MC(t));
         CO2pkCalc_1.. cdemsk_1 =e= cdems_1/sum(t, DEM_1(t));

* ### VRE ###
* Equipment Capacity Calculation of VRE
         OutputVRE_1(vre,t).. opvre_1(vre,t) =e= VRETR_1(vre,t)*(sfvre_1(vre)*MC(t));
         EqpCapacityVRE_1(vre).. cpvre_1(vre) =e= sfvre_1(vre)*CBVRE_1(vre);

* VRE Cost
         VRECostCalc_1.. vrecost_1 =e= sum(vre, (cpvre_1(vre)-CEVRE_1(vre))*(10**3)*CCVRE(vre)
                                            *DR/(1-((1+DR)**(-PBPVRE(vre)))))/(10**6)
                                    + sum(vre, (cpvre_1(vre)*(10**3)*CCVRE(vre)*OMVRE(vre)/100))/(10**6);

* ### Energy Storage ###
* Power Storage Amount Calculation
         StorageES_1(es,t).. stes_1(es,t) =e= stes_1(es,t-1)*(1-(SDES(es)*MC(t)/24)/100)
                                          + cses_1(es,t)*(EFFES(es)*MC(t))/100
                                          - dces_1(es,t)
                                          + INITES_1(es,t);

         StoragePHS_1(phs,t).. stphs_1(phs,t) =e= stphs_1(phs,t-1)
                                              + csphs_1(phs,t)*(EFFPHS(phs)*MC(t))/100
                                              - dcphs_1(phs,t)
                                              + INITPHS_1(phs,t);

* Equipment Capacity Calculation of ES
         EqpCapacityES_1(es,t).. cpes_1(es)*DOD(es)/100*MC(t) =g= stes_1(es,t);
         MXCapacityES_1(es).. cpes_1(es) =l= CLES_1(es);

* ES Cost
         ESCostCalc_1.. escost_1 =e= sum(es, (cpes_1(es)-CEES_1(es))*(10**3)*CCES(es)
                                       *DR/(1-((1+DR)**(-PBPES(es)))))/(10**6)
                                 + sum(es, (cpes_1(es)*(10**3)*CCES(es)*OMES(es)/100))/(10**6)
                                 + sum(phs, (CPPHS_1(phs)*(10**3)*CCPHS(phs)*OMPHS(phs)/100))/(10**6);

* ### H2 System ###
```

```
* Total Cost of H2 Generation, Transportation and Storage
        H2Cost_1.. hycost_1 =e= sum(hts, (cphg_1(hts)-CEHG_1(hts))*(10**3)*CCHG(hts)
                            *DR/(1-((1+DR)**(-PBPHG(hts))))))/(10**6)
                    + sum(hts, (cpht_1(hts)-CEHT_1(hts))*(10**3)*CCHT(hts)*DR/(1-((1+DR)**(-PBPHT(hts))))))/(10**6)
                    + (cphs_1-CEHS_1("HTS1"))*(10**3)*CCHS("HTS1")*DR/(1-((1+DR)**(-PBPHS("HTS1"))))/(10**6)
                    + sum(hts, (cphg_1(hts)*(10**3)*CCHG(hts)*OMHG(hts)/100))/(10**6)
                    + sum(hts, (cpht_1(hts)*(10**3)*CCHT(hts)*OMHT(hts)/100))/(10**6)
                    + (cphs_1*(10**3)*CCHS("HTS1")*OMHS("HTS1")/100)/(10**6)
                    + sum((hts,t), (hten_1(hts,t)*(10**3)*(TCHT(hts)*MC(t))))/(10**6)
;

* H2 Generation as per Energy [MWh]
        H2Generation_1(hts,t).. hgen_1(hts,t) =e= cshg_1(hts,t)*(EFFHG(hts)*MC(t)/100);

* Equipment Capacity Calculation of HG
        EqpCapacityHG_1(hts,t).. cphg_1(hts)*MC(t) =g= cshg_1(hts,t);
        MXCapacityHG_1(hts).. cphg_1(hts) =l= CLHG_1(hts);

* H2 Carrier Ammount [MWh]
        H2CarrierAmmount_1(hts,t).. hten_1(hts,t) =e= hgen_1(hts,t)*(EFFHT(hts)*MC(t)/100);

* Equipment Capacity Calculation of H2 Transportation
        EqpCapacityHT_1(hts,t).. cpht_1(hts)*MC(t) =g= hten_1(hts,t);
        MXCapacityHT_1(hts).. cpht_1(hts) =l= CLHT_1(hts);

* Power Storage Amount Calculation
        StorageHS_1(t).. hsen_1(t) =e= hsen_1(t-1)*(1-SDHS("HTS1")/24/100)
                                   + hten_1("HTS1",t) - dchs_1(t)
                                   + INITHTS_1(t);
        EqpCapacityHS_1(t).. cphs_1*MC(t) =g= hsen_1(t);
        MXCapacityHS_1.. cphs_1 =l= CLHS_1("HTS1");

* H2 Consumption of GTCC [GJ]
        H2ConsGT_1(t).. dchs_1(t)*3.6 + dchs_ia1(t)*3.6 =e= sum(gt,fcg_1(gt,t)) - fclng_1(t);

* ### Other Power Plant ###
        OPPCostCalc_1.. oppcost_1 =e= sum(top, (CPOPP_1(top)-CEOPP_1(top))*1000*CCOPP(top)
                                   *DR/(1-((1+DR)**(-PBPOPP(top)))))/(10**6)
                              + sum(top, (CNOPP_1(top))*1000*CCOPP(top)
                                   *DR/(1-((1+DR)**(-PBPOPP(top)))))/(10**6)
                              + sum(top, (CPOPP_1(top))*1000*CCOPP(top)*(OMOPP(top)/100)/(10**6));

* << Other Western Japan >>
* ! Abbreviated for the appendix. The same codes as “Kansai Area.”

* << Inter-Area for H2 System >>
* Cost of H2 Storage
        H2Cost_ia.. hycost_ia =e= (cphs_ia-CEHS_ia)*(10**3)*CCHS("HTS2")*DR/(1-((1+DR)**(-PBPHS("HTS2"))))/(10**6)
                    + (cphs_ia*(10**3)*CCHS("HTS2")*OMHS("HTS2")/100)/(10**6)
;

* Power Storage Amount Calculation
        StorageHS_ia(t).. hsen_ia(t) =e= hsen_ia(t-1)*(1-SDHS("HTS2")/24/100)
                                + hten_1("HTS2",t) + hten_2("HTS2",t)
                                - dchs_ia1(t) - dchs_ia2(t)
                                + INITHTS_ia(t);

        EqpCapacityHS_ia(t).. cphs_ia*MC(t) =g= hsen_ia(t);
        MXCapacityHS_ia.. cphs_ia =l= CLHS_ia;


* << Common >>
        TotalCost.. tc =e= cost_1 + cost_2 + hycost_ia;

        TotalTPCost.. tctp =e=   tpcost_1 + tpcost_2;

        TotalFuelCost.. tfc =e= flcost_1 + flcost_2;

        TotalVRECost.. tcvre =e= vrecost_1 + vrecost_2;

        TotalESCost.. tces =e= escost_1 + escost_2;

        TotalH2Cost.. tchy =e= hycost_1 + hycost_2 + hycost_ia;
```

```
            TotalCO2Emis.. tcde =e= cdems_1 + cdems_2;

Model demo / all /;

* === Solve ===
option lp = MINOS;
solve demo using lp minimizing z;
```

Appendix B. Supplement of Chapter 3

B.1 Application of reference point, value function and weighting function

Essential characteristics of the Reference Point, Value Function and the Weighting Function [46,47] focused on this chapter are as follows:

B.1.1 Reference point

Values are evaluated by gains and losses relative to an RFP, and the RFP can be affected and shifted by the expectation of the decision-maker. This means that change in RFP will bring different value for the decision-maker even though the decision-maker acquires the same outcome from their decision.

$$x = x_{oc} - x_{rp} \tag{B.1}$$

where x is the gain/loss relative to the RFP, x_{oc} is the outcome of the option, and x_{rp} is the RFP.

B.1.2. Value function

The value function is defined as equation (B.2), and the expected shape is shown in **Figure B.1**. This function expresses that the decision-maker tends to be risk-averse in the positive domain ($x \geq 0$) and be risk-seeking in the negative domain ($x < 0$).

$$v(x) = \begin{cases} x^{\alpha} & (x \geq 0) \\ -\lambda(-x)^{\beta} & (x < 0) \end{cases} \tag{B.2}$$

The median exponent α for gains of 0.88, β for losses of 0.88, and the median λ of 2.25 were used in this chapter, which was shown by Tversky and Kahneman [46,47].

B.1.3. Weighting function

Though there are several studies on definitions of the Weighting Function [155–157], we applied the Weighting Function that was given by Tversky and Kahneman [47] since their definition is the most commonly used. The Value of each outcome is given by multiplying the Value Function by the Weighting Function (B.3), which expresses the subjective probability of each outcome, as shown in (B.4) and **Figgure B-2**. The median values γ of 0.61 for positive x_i (gains) and 0.69 for negative x_i (losses) are used in this study, which was shown by Tversky and Kahneman [47].

$$V(x_1, p_1 \cdots x_n, p_n) = \sum_{i=0}^{n} w(p_i) v(x_i) \tag{B.3}$$

$$w(p) = \frac{p^{\gamma}}{\left\{p^{\gamma} + (1-p)^{\gamma}\right\}^{\frac{1}{\gamma}}} \tag{B.4}$$

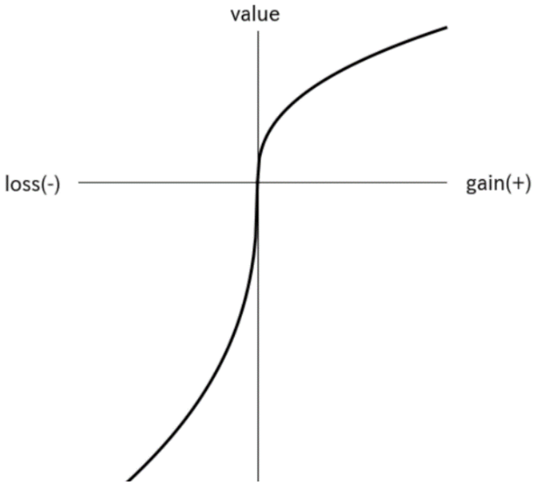

Figure B.1. The Value Function (Based on [47])

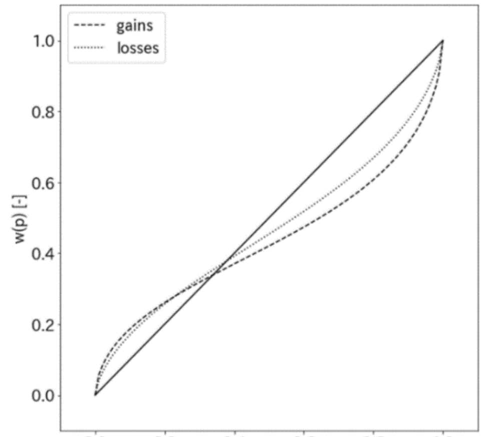

Figure B.2. The Weighting Function (Based on [47])

B.2 Definition of NPV and the other outputs

Net Present Value (NPV)

NPV in this study is defined as follows:

$$npv_i = \sum_{y=1}^{20} \frac{cf_{iy}}{(1+DR)^y} - \sum_{j=1}^{2} CAPEX_j \tag{B.5}$$

$$cf_{iy} = \sum_{t=1}^{8760} \sum_{j=1}^{2} \{(sp_{ity} + FIP_j - mc_{ijy}) \times op_{ijty}\} \tag{B.6}$$

where, parameters of capital letters mean exogenous variables or fixed values, and parameters of lower cases are endogenous variables. Index of i, j, t, and y express the number of trials in iterative calculations of the model, technologies (1: PV, 2: Wind), time, and year respectively. The npv_i is total NPV [yen], cfiy is cash flow earned in the energy market, DR is the discount rate (set as 5% considering Weighted Average Cost of Capital (WACC) of electric utility companies in Japan [158]), $CAPEX_j$ is the initial cost of each technology, spity is spot price in the energy market, FIP_j is the price of FIP, mcijy is the marginal cost of power generation [yen/kWh], and opijty is the power output of each technology [kWh].

The following equations give the expected value and standard deviation of NPV.

$$\exp_{NPV} = \sum_{i=1}^{N} npv_i \Big/ N \tag{B.7}$$

$$sd_{NPV} = \sqrt{\frac{1}{i} \sum_{i=1}^{N} (npv_i - \exp_{NPV})^2} \tag{B.8}$$

where, N is the total number of trials in iterative calculations (=1,000 times in this study). exp_{NPV} and sd_{NPV} mean the expected value and standard deviation of NPV.

Value at Risk (VaR) and Conditional Value at Risk (CVaR)

VaR is one type of expected shortfall, and the "VaR at q%" is defined as the expected income in the worst q% of cases. CVaR is the average of values below VaR cases. In this study, 1,000 cases of NPV are given for each calculation by the simulation in line with probability distributions, and CVaR calculated based on “VaR at 5%” is used; CVaR of NPV is the average of the 5% lowest cases of NPVi. CVaR is interpreted as the expected NPV, which Company 2 earns in the worst-case scenario for each calculation in this study.

B.3 Properties of Technology

Properties of Each Technology are shown in the following table.

Table B.1. Properties of technologies

Item	Unit	Technology	Value	Remarks
Construction Cost	[yen/kW]	GTCC (Natural Gas)	120,000	[92] Cost for abolishing facilities is not considered.
		PV	273,500	
		Wind (On-shore)	287,000	
Operation & Maintenance	[%/Year]	GTCC (Natural Gas)	3.0	[92]
		Steam Power (Oil)	3.2	
		Steam Power (Coal)	4.0	
		Nuclear	5.2	
		PV	1.2	
		Wind (On-shore)	2.1	
Gross Plant Efficiency (LHV)	[%-LHV]	GTCC (Natural Gas, Existing)	51.5	Based on [92]
		GTCC (Natural Gas, Replaced)	58.6	
		Steam Power (Oil)	37.5	
		Steam Power (Coal)	40.8	
Payback Period	[Year]	GTCC	15	[92]
		PV	10	
		Wind (On-shore)	10	
Lifetime	[Year]	GTCC	40	[92]
		PV	20	
		Wind (On-shore)	20	
CO$_2$ Emission Coefficient	[t-CO$_2$/t]	GTCC (Natural Gas)	2.7	[152]
		Steam Power (Oil)	3.4	
		Steam Power (Coal)	2.3	

calculated based on “VaR at 5%” is used; CVaR of NPV is the average of the 5% lowest cases of NPVi. CVaR is interpreted as the expected NPV, which Company 2 earns in the worst-case scenario for each calculation in this study.

B.4 Calculation results of each case

Digital data of calculation results in each case are shown in **Tables B.2**, **B.3**, **B.4**, **B.5**, and **B.6**, which are corresponding to **Figures 3.9**, **3.10**, **3.11**, **3.12**, and **3.13** in Section 3.3, respectively.
("Exp." means "Expected," "SD" means "Standard Deviation" in the tables.)

Table B.2. Calculation results of Case 1 & 2 (corresponding to **Figure 3.9**)

Scenario	Case		1 (Investments in PV)					2 (Investments in Wind)				
	Total Capacity	Unit	0	1,000	3,000	5,000	7,000	0	1,000	3,000	5,000	7,000
FIP-Low	Exp. NPV	Billion yen	372.9	335.8	221.1	67.7	-129.6	372.9	339.2	212.3	-15.5	-316.1
	Exp.Value (Ref_EXP)	-	0.0	-37.7	-123.6	-225.9	-346.1	0.0	-37.0	-126.7	-270.2	-461.6
	Exp.Value (Ref_CVaR)	-	0.0	0.3	-84.1	-188.6	-312.2	0.0	0.6	-87.9	-232.5	-426.0
	SD of NPV	Billion yen	26.0	40.0	65.7	91.7	105.8	26.0	48.1	97.7	141.0	167.7
	CVaR of NPV	Billion yen	319.0	253.7	88.6	-123.1	-342.8	319.0	243.0	9.7	-290.1	-642.1
FIP-Mid	Exp.NPV	Billion yen	372.9	363.3	308.4	217.0	69.2	372.9	415.0	428.9	357.3	188.9
	Exp.Value (Ref_EXP)	-	0.0	-19.2	-61.7	-129.9	-209.2	0.0	9.9	-0.4	-38.4	-135.9
	Exp.Value (Ref_CVaR)	-	0.0	14.2	-24.1	-90.5	-173.4	0.0	36.7	29.0	-8.6	-104.0
	SD of NPV	Billion yen	26.0	41.3	69.1	95.8	117.6	26.0	53.3	128.7	189.6	217.7
	CVaR of NPV	Billion yen	319.0	277.2	172	18.7	-174.9	319.0	305.4	163.3	-3.6	-230.5
FIP-High	Exp.NPV	Billion yen	372.9	407.8	440.9	441.7	367.8	372.9	466.2	580.2	604.4	520.4
	Exp.Value (Ref_EXP)	-	0.0	9.0	17.5	0.7	-38.1	0.0	35.4	62.8	65.6	22.4
	Exp.Value (Ref_CVaR)	-	0.0	34.7	43.7	29.1	-8.6	0.0	57.9	85.7	90.2	49.1
	SD of NPV	Billion yen	26.0	41.8	74.4	107.9	134.3	26.0	62.8	148.7	221.3	269.9
	CVaR of NPV	Billion yen	319.0	324.7	294.4	201.4	89.5	319.0	346.0	282.6	164.6	-21.0

Table B.3 Calculation results of Case 3 & 4 (corresponding to **Figure 3.10**)

Scenario	Case		3 (Investments in PV with FIP-Low)					4 (Investments in Wind with FIP-Low)				
	Total Capacity	Unit	0	1,000	3,000	5,000	7,000	0	1,000	3,000	5,000	7,000
wRP _NC60	Exp. NPV	Billion yen	372.9	335.8	221.1	67.7	-129.6	372.9	339.2	212.3	-15.5	-316.1
	Exp. Value (Ref_EXP)	-	0.0	-37.7	-123.6	-225.9	-346.1	0.0	-37.0	-126.7	-270.2	-461.6
	Exp. Value (Ref_CVaR)	-	0.0	0.3	-84.1	-188.6	-312.2	0.0	0.6	-87.9	-232.5	-426.0
	SD of NPV	Billion yen	26.0	40.0	65.7	91.7	105.8	26.0	48.1	97.7	141.0	167.7
	CVaR of NPV	Billion yen	319.0	253.7	88.6	-123.1	-342.8	319.0	243.0	9.7	-290.1	-642.1
wRP _NC40	Exp. NPV	Billion yen	464.6	451.3	413.2	354.3	255.5	464.6	483.3	475.5	413.6	258.7
	Exp. Value (Ref_EXP)	-	0.0	-21.6	-52.2	-100.6	-154.2	0.0	-1.9	-15.9	-63.5	-151.0
	Exp. Value (Ref_CVaR)	-	0.0	16.9	-10.6	-53.7	-112.7	0.0	30.7	19.7	-23.6	-112.0
	SD of NPV	Billion yen	32.1	45.6	78.8	96.7	122.5	32.1	56.1	119.1	186.9	219.9
	CVaR of NPV	Billion yen	400	360	255	159	17	400	377	254	54	-174
woRP _NC60	Exp. NPV	Billion yen	335.1	285.8	154.1	1.3	-193.1	335.1	284.3	124.1	-111.3	-415.4
	Exp. Value (Ref_EXP)	-	0.0	-47.1	-148.3	-241.6	-358.6	0.0	-50.6	-150.1	-310.9	-501.0
	Exp. Value (Ref_CVaR)	-	0.0	-5.8	-105.4	-204.1	-323.9	0.0	-12.2	-115.8	-277.0	-469.8
	SD of NPV	Billion yen	27.9	37.3	59.9	82.7	101.3	27.9	45.0	96.4	135.9	160.6
	CVaR of NPV	Billion yen	278.7	211.4	31.7	-163.0	-402.4	278.7	196.6	-64.5	-372.5	-730.2

Table B.4 Calculation results of Case 5 & 6 (corresponding to **Figure 3.11**)

Scenario	Case		5 (with FIP-Low)					6 (with FIP-High)				
	Total Capacity	Unit	0	1,000	3,000	5,000	7,000	0	1,000	3,000	5,000	7,000
PV _woOE	Exp. NPV	Billion yen	372.9	335.8	221.1	67.7	-129.6	372.9	407.8	440.9	441.7	367.8
	Exp. Value (Ref_EXP)	-	0.0	-37.7	-123.6	-225.9	-346.1	0.0	9.0	17.5	0.7	-38.1
	Exp. Value (Ref_CVaR)	-	0.0	0.3	-84.1	-188.6	-312.2	0.0	34.7	43.7	29.1	-8.6
	SD of NPV	Billion yen	26.0	40.0	65.7	91.7	105.8	26.0	41.8	74.4	107.9	134.3
	CVaR of NPV	Billion yen	319.0	253.7	88.6	-123.1	-342.8	319.0	324.7	294.4	201.4	89.5
WIND _woOE	Exp. NPV	Billion yen	372.9	339.2	212.3	-15.5	-316.1	372.9	466.2	580.2	604.4	520.4
	Exp. Value (Ref_EXP)	-	0.0	-37.0	-126.7	-270.2	-461.6	0.0	35.4	62.8	65.6	22.4
	Exp. Value (Ref_CVaR)	-	0.0	0.6	-87.9	-232.5	-426.0	0.0	57.9	85.7	90.2	49.1
	SD of NPV	Billion yen	26.0	48.1	97.7	141.0	167.7	26.0	62.8	148.7	221.3	269.9
	CVaR of NPV	Billion yen	319.0	243.0	9.7	-290.1	-642.1	319.0	346.0	282.6	164.6	-21.0
MIX1 _woOE	Exp. NPV	Billion yen	372.9	340.4	240.3	93.0	-84.7	372.9	443.3	542.0	593.5	601.0
	Exp. Value (Ref_EXP)	-	0.0	-35.3	-116.8	-221.1	-312.7	0.0	26.6	60.5	73.7	63.9
	Exp. Value (Ref_CVaR)	-	0.0	3.6	-72.1	-178.6	-276.2	0.0	49.4	81.1	95.5	85.9
	SD of NPV	Billion yen	26.0	40.7	69.9	97.9	121.4	26.0	46.0	92.9	144.5	180.7
	CVaR of NPV	Billion yen	319.0	257.5	99.8	-106.1	-330.0	319.0	350.6	356.0	305.5	228.7
MIX2 _woOE	Exp. NPV	Billion yen	372.9	339.1	237.0	106.4	-70.5	372.9	426.6	512.1	550.3	563.6
	Exp. Value (Ref_EXP)	-	0.0	-36.5	-114.6	-197.0	-320.3	0.0	18.9	49.1	63.9	58.6
	Exp. Value	-	0.0	1.1	-75.0	-160.9	-285.3	0.0	43.1	70.0	86.5	80.7

	(Ref_CVaR)											
	SD of NPV	Billion yen	26.0	40.1	67.5	89.2	116.5	26.0	43.0	78.6	111.7	155.9
	CVaR of NPV	Billion yen	319.0	258.8	102.5	-79.5	-305.3	319.0	339.4	350.4	330.3	262.1
MIX3 _woOE	Exp. NPV	Billion yen	372.9	338.0	231.6	60.2	-126.4	372.9	451.4	550.3	610.7	611.0
	Exp. Value (Ref_EXP)	-	0.0	-37.8	-115.0	-211.3	-345.6	0.0	29.3	64.5	78.0	79.1
	Exp. Value (Ref_CVaR)	-	0.0	-1.2	-77.3	-177.2	-311.3	0.0	50.6	84.0	97.1	100.4
	SD of NPV	Billion yen	26.0	42.8	82.2	114.4	134.2	26.0	50.4	106.1	166.8	198.0
	CVaR of NPV	Billion yen	319.0	251	69	-167	-379	319.0	353	338	283	227

Table B.5 Calculation results of Case 7 & 8 (corresponding to **Figure 3.12**)

Scenario	Case		7 (Investments in PV with FIP-Low)					8 (Investments in Wind with FIP-Low)				
	Total Capacity	Unit	0	1,000	3,000	5,000	7,000	0	1,000	3,000	5,000	7,000
PV _woOE (Case 7) WIND _woOE (Case 8)	Exp NPV	Billion yen	372.9	335.8	221.1	67.7	-129.6	372.9	339.2	212.3	-15.5	-316.1
	Exp Value (Ref_EXP)	-	0.0	-37.7	-123.6	-225.9	-346.1	0.0	-37.0	-126.7	-270.2	-461.6
	Exp Value (Ref_CVaR)	-	0.0	0.3	-84.1	-188.6	-312.2	0.0	0.6	-87.9	-232.5	-426.0
	SD of NPV	Billion yen	26.0	40.0	65.7	91.7	105.8	26.0	48.1	97.7	141.0	167.7
	CVaR of NPV	Billion yen	319.0	253.7	88.6	-123.1	-342.8	319.0	243.0	9.7	-290.1	-642.1
PV _wOE (Case 7) WIND _wOE (Case 8)	Exp NPV	Billion yen	372.9	345.0	279.7	224.6	157.8	372.9	341.2	261.2	168.0	65.7
	Exp Value (Ref_EXP)	-	0.0	-32.5	-92.9	-138.4	-170.8	0.0	-36.5	-113.5	-179.0	-249.4
	Exp. Value (Ref_CVaR)	-	0.0	6.8	-51.8	-98.4	-135.5	0.0	-1.5	-74.6	-143.8	-215.5
	SD of NPV	Billion yen	26.0	32.8	65.9	92.9	122.7	26.0	40.0	93.2	150.3	201.0
	CVaR of NPV	Billion yen	319.0	276.1	106.5	-70.7	-259.5	319.0	250.8	35.9	-227.1	-493.7

Table B.6 Calculation results of Case 9 & 10 (corresponding to **Figure 3.13**)

Scenario	Case		9 (Investments in PV with FIP-High)					10 (Investments in PV with FIP-High)				
	Total Capacity	Unit	0	1,000	3,000	5,000	7,000	0	1,000	3,000	5,000	7,000
PV _woOE (Case 9) WIND _woOE (Case 10)	Exp. NPV	Billion yen	372.9	407.8	440.9	441.7	367.8	372.9	466.2	580.2	604.4	520.4
	Exp. Value (Ref_EXP)	-	0.0	9.0	17.5	0.7	-38.1	0.0	35.4	62.8	65.6	22.4
	Exp. Value (Ref_CVaR)	-	0.0	34.7	43.7	29.1	-8.6	0.0	57.9	85.7	90.2	49.1
	SD of NPV	Billion yen	26.0	41.8	74.4	107.9	134.3	26.0	62.8	148.7	221.3	269.9
	CVaR of NPV	Billion yen	319.0	324.7	294.4	201.4	89.5	319.0	346.0	282.6	164.6	-21.0
PV _wOE (Case 9) WIND _wOE (Case 10)	Exp. NPV	Billion yen	372.9	360.9	313.3	238.4	142.3	372.9	409.0	430.6	394.4	327.7
	Exp. Value (Ref_EXP)	-	0.0	-19.7	-62.1	-115.5	-173.7	0.0	10.2	8.7	-22.1	-72.5
	Exp. Value (Ref_CVaR)	-	0.0	14.0	-24.1	-77.4	-136.6	0.0	35.1	31.9	6.4	-42.4
	SD of NPV	Billion yen	26.0	37.9	67.8	96.2	141.4	26.0	49.3	116.7	174.5	216.9
	CVaR of NPV	Billion yen	319.0	285.7	178.0	41.9	-105.4	319.0	315.1	204.8	43.8	-126.6

Appendix C. Supplement of Chapter 4

C.1 Formulation of TF-IDF

The TF-IDF introduced in Section 4.2.4 was formulated as follows [142–144];

$$tf(t,d) = \frac{n_{t,d}}{\sum_{s \in d} n_{s,d}} \tag{C.1}$$

$$idf(t) = \log \frac{N}{1 + df(t)} \tag{C.2}$$

$$tfidf(t,d) = tf(t,d) \times ifd(t) \tag{C.3}$$

where *tf(t,d)* is the TF value of word *t* in document *d*, a set of words, $n_{t,d}$ is the number of occurrences of word *t* in document *d*, *s* is an element of document *d* that is a set of words, and $n_{s,d}$ is the number of occurrences of word element *s* in document *d*. The *idf(t)* is the IDF value of the word *t*, *N* is the number of documents, *df(t)* is the number of documents containing the word *t*, and *tfidf(t,d)* is the TF-IDF value of the word *t* in document *d*.

C.2 Principal component analysis results

As described in Section 4.2.3, principal component analysis (PCA) was adopted as a method for dimensionality reduction of features. In this section, the results of the principal component analysis of Case 2 are shown, and it is supplemented that the features and dimension reduction used in Chapter 4 are appropriate.

Figure C.1 shows the number of principal components on the horizontal axis, and the cumulative value of the data variance with respect to the number of principal components on the vertical axis. In PCA, dimension reduction is performed by projecting onto a new subspace that maximizes the variance of the data, and it can be seen that the three principal components (three dimensions) contain 75% of the total variance. That is, the dimensionality reduction from 10-dimensional features to three principal components (three dimensions) is effective to represent features of data in this chapter.

Figure C.2 plots the contribution of each feature to the principal components, with the first principal component (PC1) on the horizontal axis, the second principal component (PC2) on the vertical axis, and the third principal component (PC3) on the color bar. It can be seen that the 10-dimensional features adopted in this chapter widely cover the contribution of each principal component in the positive to the negative range.

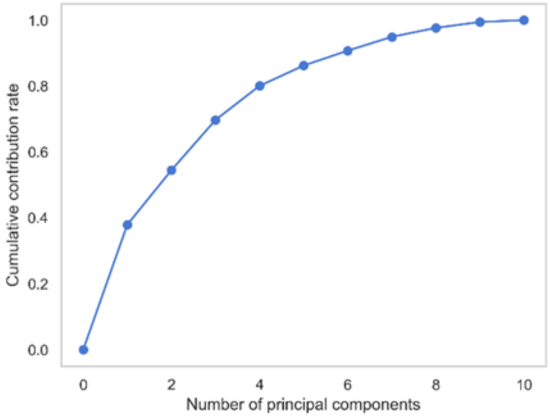

Figure C.1. Cumulative contribution rate of with respect to the number of principal components (Case 2)

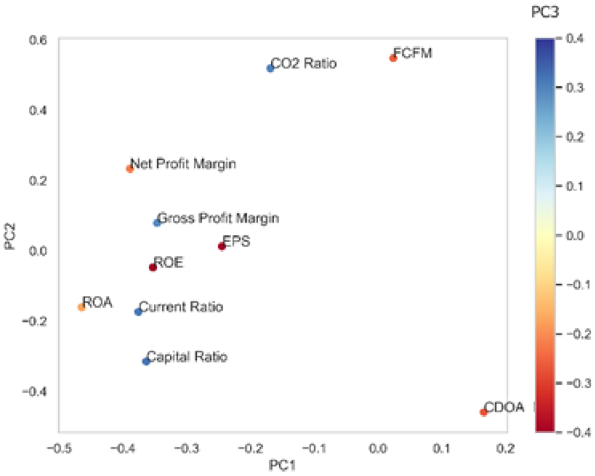

Figure C.2. Contribution of each feature to the principal components, with PC1 on the horizontal axis, PC2 on the vertical axis, PC3 on the color bar (Case 2).

C.3 Evaluation of the number of clusters

Companies in the scope of this chapter were clustered by the k-means++ method using financial and CO_2 indexes as features. As described in Section 4.2.3, the number of clusters was adopted as six. **Figure C.3** shows the number of clusters on the horizontal axis and the sum of squared errors in the clusters on the vertical axis. The elbow method evaluates the number of clusters by the trend of this graph. The elbow method estimates that the number of clusters is appropriate where the slope of the change in the sum of squared errors in the cluster with respect to the change in the number of clusters begins to increase. The appropriate number of clusters was expected to be six from **Figure C.3**, and it was confirmed that the characteristics of the company's energy transition could be effectively extracted with the six clusters by actually performing clustering. In the k-means ++ method, the number of clusters is determined by the analyst. Therefore it should be noted that the selection of the number of clusters involves some subjectivity.

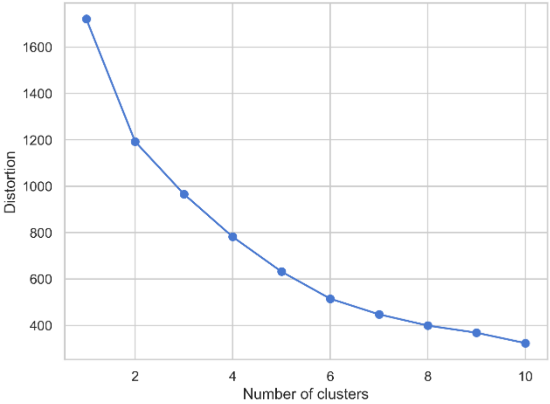

Figure C.3. Evaluation of the number of clusters by the elbow method (Case 2)

List of Publications

Journal Papers

CHAPTER 2.

R. Gotoh, T. Tezuka, Study on Power Supply System for Large Scale Renewable Energy Introduction under Different Strategies of Existing Power Plant Replacement, *Japan Society of Energy and Resources*, 2020, Vol. 41, No. 2, 38–50, doi:10.24778/jjser.41.2_38.

CHAPTER 3.

R. Gotoh, T. Tezuka, B. C. McLellan, Study on Behavioral Decision Making by Power Generation Companies regarding Energy Transitions under Uncertainty, *Energies* (under review), 2021

CHAPTER 4.

R. Gotoh, T. Tezuka, A Study on the Possibility of Company's Energy Transition based on the Analysis of Financial and Business Reports, *Japan Society of Energy and Resources*, 2020, Vol. 41, No. 6, 307–317, doi: 10.24778/jjser.41.6_307.

Conferences

1. R. Gotoh, T. Tezuka, "Study on Power Supply System for Large Scale Renewable Energy Introduction under Different Strategies of Existing Power Plant Replacement", *Japan Society of Energy and Resources 38th Conference*, Tokyo, August 2019
2. R. Gotoh, T. Tezuka, "Study on Possibility of Company's Energy Transition based on Financial and Business Report Analysis", *Japan Society of Energy and Resources 39th Conference*, July 2020 (Web conference)
3. R. Gotoh, T. Tezuka, "Study of the Behavioral Decision Making by Power Generation Companies regarding Energy Transition under Uncertainty", *the 37th Conference for Energy System, Economics and Environment, Japan Society of Energy and Resource*, January 2021 (Web conference)