Studies on dynamic vulnerability based on sudden disturbances in the context of diversity in power mix

Shoki Kosai

Studies on dynamic vulnerability based on sudden disturbances in the context of diversity in power mix

Shoki Kosai

A dissertation submitted to
the Graduate School of Energy Science of Kyoto University
in partial fulfillment of the Degree of Doctor of Energy Science

Kyoto, Japan
2020

Extended abstract

The increase in global energy demand arising from the rapid expansion of world population and the heavy industrialization has drastically changed the global energy landscape in recent decades and has critically threatened the energy security. Since energy is fundamental to human well-being and sustainable development, improvement of energy security is of paramount importance, and numerous researchers have attempted to analyze energy security in a quantitative way.

This study pays attention to the vulnerability-based approach, under which the vulnerability potentially contained in a vital energy system is analyzed with a focus on a combination of its exposure to risks and resilience. Although the concept of vulnerability-based approach is recognized as one of the methodological approaches, quantitative evaluation of energy security by using such approach has hardly been conducted hitherto.

As a starting point of addressing the vulnerability-based approach in the energy security narrative, therefore, this study particularly focuses on the vulnerability potentially contained in a vital electricity system based on the relationship between an interruption of an electricity supply source as a feature of risks and diversity in power mix as a feature of resilience. Diversity in power mix is a fundamental aspect of electricity security, which is a major energy policy measure.

In the quantitative evaluation of diversity in power mix, it has been conventionally derived on the basis of static vulnerability under the long-term and steady state, by accounting for the share of energy generation by power supply source. Diversity in power mix has been considered as a factor in the long-term energy security, whilst it is essential that dynamic sudden supply interruptions under the short-term and unsteady state are theoretically and qualitatively relevant to diversity in power mix as well. However, the dynamic vulnerability has yet to be quantitatively evaluated in the context of diversity in power mix as a factor of the short-term energy security. In addition, the number of existing indicators for assessing short-term energy security are limited, and such indicators do not sufficiently cover the concept of dynamic vulnerability in the context of diversity in power mix.

In summary, there are mainly three research gaps in the context of diversity in power mix, including 1) few quantitative studies on vulnerability-based approach in the energy security narrative, 2) no quantitative evaluation of diversity in power mix considering both static and dynamic vulnerability, and 3) limited number of indicators for evaluating short-term energy security.

While aspects of diversity in power mix have been widely studied in detail by a wide range of scholars accounting for energy generation by power sources from the perspective of static vulnerability, this study aims to fill the research gaps in the studies regarding the dynamic vulnerability of an electricity system against the disruption of continuous electricity supply caused by sudden disturbances on an electricity supply. As such, the objective of this thesis is

1. **To conceptualize the dynamic vulnerability**
2. **To develop the methodology for its quantification**
3. **To analyze the static and dynamic vulnerability of vital electricity system in the context of diversity in power mix.**

The central research question for this study is: **what is the difference of trend between static and dynamic vulnerability in the context of diversity in power mix in energy security?** This question would be further broken down into the related sub-questions as follows:

Sub-Q.1: What is the concept of dynamic vulnerability proposed in this study?

Sub-Q.2: How can the dynamic vulnerability be quantified in the context of diversity in power mix?

Sub-Q.3: What index dedicated for the dynamic vulnerability should be developed?

Sub-Q.4: How can the developed index dedicated for dynamic vulnerability be applied?

To answer these research questions and to accomplish the objective of the thesis, the analytical portion of this thesis is divided into four main sections.

The first section conceptualizes the static and dynamic vulnerability in the context of diversity in power mix. As the boundary of diversity in power mix, the static vulnerability is relevant to the stage of primary energy resource procurement, whereas the dynamic vulnerability corresponds to the stage of power generation at facilities. Considering that the concept of static vulnerability is based on sufficiency of power generation to meet demand, the dynamic vulnerability is interpreted in this study as a degree in which the system maintains supply capability to generate sufficient power for meeting demand even after an occurrence of sudden interruption of electricity supply source. The system which maintains the minimum supply capability can remain self-sufficient. This is relevant to sub-Q.1.

The second section develops the methodology for evaluating short-term vulnerability in the context of diversity in power mix. Such methodology covered the several characteristics to be assessed, including sufficiency, a focus on the generation stage under HL-1, vulnerability potentially contained in the system, a focus on each power source, and consideration of time-series notion. The three major components of sudden disturbances were introduced, that is: magnitude, duration and instant of failure. The methodological process was established to identify a threshold of magnitude and duration of sudden disturbances at a given instant of time under which the power system can maintain the supply capability in a self-sufficient manner. The greater threshold corresponds to the lower dynamic vulnerability of power system to supply disruptions due to sudden disturbances. This is relevant to sub-Q.2.

The third section conducts the assessment of dynamic vulnerability by using the developed methodology as case studies. Based on the obtained threshold of supply capability, the three types of curves were depicted. Then, the area under the depicted curve was computed to develop an index dedicated for the dynamic vulnerability. This is relevant to sub-Q.3. The developed index dedicated for the dynamic vulnerability was applied into the fictitious standalone centralized network and distribution network as case studies. Referring to a certain electricity system to some extent in Japan, the combination between demand and supply capacity was changed under the condition where sufficiency is secured in a static state. The time range assessed in this study focused on a one-day snapshot. In particular, the sudden disturbances on nuclear energy use in centralized power network and on renewables and storage technology in distributed network were addressed as case studies. This study demonstrated its applicability through cost-effectiveness analysis. This is relevant to sub-Q.4.

By extending and synthesizing the aforementioned sections, the fourth section compares the static and dynamic vulnerability in the fictitious standalone distributed and centralized power network. In both fictitious distributed network and centralized network adopted in this study, the comparison between static and dynamic vulnerability exhibited a significantly different trend. This is relevant to the central question.

Notably, this study would contribute to a) highlighting a new concern on nuclear power use, b) quantitative presentation of significant role of storage technology in securing short-term power supply, c) Establishment of a new index dedicated for short-term energy security, d) direct adoption of developed methodology and index to any other power system networks, and e) identifying new insights on diversity in power mix.

The different trend between static and dynamic vulnerability would raise a necessity to reconsider the design policy of the electricity supply system in terms of evaluating diversity in power mix from the perspective of not only static vulnerability but also dynamic vulnerability. Relying only on energy generation and capacity, which is the conventional approach for long-term diversity evaluation, may potentially bear significant risk overlooking the hidden factors associated with the dynamic vulnerability. The major results and findings of this study shall add a new view to energy security assessment and sustainable energy resource supply strategy, which is becoming more important in energy policy design.

Acknowledgement

First of foremost, I would like to express my deep gratitude and appreciation to my project supervisor, Prof. Dr. Hironobu Unesaki for his suggestions, guidance and support with the research and writing of the dissertation throughout my phd study. His support, understanding and expertise, and all other help he has given me in the last years make this a fulfilling and enjoyable experience.

I would also like to thank the other members of my doctoral review committee: Prof. Keiichi Ishihara and Prof. Ken Kurosaki who provided invaluable comments and suggestions for improvements of the quality of the thesis.

I would like to send my regards and appreciations for the assistances and supports from Prof. Eiji Yamasue, Ritsumeikan University.

I also want to thank my family and friends for their continuous support and encouragement throughout my study.

Table of Contents

List of figures

List of tables

CHAPTER 1 : Introduction

1.1 Energy security and diversity in power mix

The increase in global energy demand arising from the rapid expansion of world population and the heavy industrialization has drastically changed the global energy landscape in recent decades and has critically threatened the energy security. Since energy is fundamental to human well-being and sustainable development, improvement of energy security is of paramount importance. In particular, energy security is a driving force of energy policy [1].

The definition of energy security differs from international institute, national government, and academic researcher. For instance of international institutes, International Energy Agency (IEA) and United Nations define energy security as "*the uninterrupted availability of energy sources at an affordable price*" [2], and "*The continuous availability of energy in varied forms, in sufficient quantities and at affordable prices*" [3], respectively. Under the scale of national government, for example, it is considered in Japan as "*to secure adequate energy at reasonable prices necessary for the people's lives, and economic and industrial activities of the country*" [4]. Winzer complied various definitions of energy security proposed by many scholars [5]. It must be mentioned that there is no concrete consensus on the definition of energy security [6, 7]. One difficulty in defining energy security is due to the fact that energy security has become increasingly complicated [8]. Energy security is dynamic in its nature and thus its definition and concept evolve with the change of the global energy landscape [1].

Numerous researchers have attempted to analyze energy security in a quantitative way. Since the concept of energy security is an abstract idea, the quantitative analysis of energy security would be considered as a conceptual-based study. The concept of energy security is a basis of other relevant disciplines such as, for example, power system engineering, in which focuses on technical practices under downstream individual situation, whilst this study addresses the quantification of energy security under the conceptual notion.

There are mainly two methodological approaches in the quantitative study of energy security, that is: dimension-based approach and vulnerability-based approach.

Dimension-based approach has been widely utilized so far, considering multiple "dimensions" which comprise the energy security in the system associated with overall energy-related issues, and then attribute representative indicators to each dimension. The selected dimensions and indicators are often expressed from the statistical data in past experiences of the real world. As an example of this approach, Vivoda proposed 11 dimensions with 44 attributes [9], while Sovacool suggested a more encompassing framework comprising of 20 dimensions with 200 indicators [10], and the performance of energy security under the national and regional level is the main subject of research. Such approach, especially the choice of dimensions and indicators, is often criticized to be somewhat arbitrary, and the choice of specific energy security indicators for any given scenario are often the subject of debate [11].

Vulnerability-based approach was developed by Cherp and Jewell [12] on the basis of a common understanding that energy security is closely associated with risk [13]. In this approach, the improvement of energy security could be described as to protect the energy system against any potential risk [14]. In this context, they have defined energy security as "*a low vulnerability of vital energy systems*" [8, 15]. Vulnerability potentially contained in an energy system is a combination of its exposure to risks and resilience. Although the concept of vulnerability-based approach originates from security studies having a long history [16], quantitative evaluation of energy security by using such approach has yet to be fully conducted. Therefore, this study attempts to quantify the vulnerability contained in a vital energy system by employing the vulnerability-based approach for well-understanding of energy security.

In the vulnerability-based approach, this study particularly focuses on diversity in the various features performing as resilience. Diversity, or the degree of variation in a system, is considered as one of the most widely accepted risk-related factors in energy security [14, 5]. The fundamental notion of diversity could be described as to prevent "putting all eggs in one basket" [17]. The over-reliance on a single resource or sub-system would alarmingly raise the risks of energy supply disruptions [18]. The increased diversity induces more options in the system [19], leading to mitigation of risks and improvement of energy security [20, 21]. Historically, the Winston Churchill administration addressed at the UK parliament that "*safety and certainty of oil lies in variety and variety alone*", when United Kingdom could not meet the requirement of rapid growth of energy demand with the indigenous coal [22]. The essential importance of diversity in securing energy security was also recognized through the experience of oil crisis in the nearly 70s. In practice, variety of characteristics of diversity has been reported so far. One of the most fundamental frameworks was developed on a basis of three components, e.g. variety, balance, and disparity [17, 23, 24]. Sovacool has proposed to use 8 components of diversity [10] and, for the quantitative analysis, Sovacool and Mukherjee have proposed to use 17 simple indicators of diversity [25]. Besides the energy narrative, diversity is a vital notion in multiple disciplines, originally developed in the field of ecology as a necessary element for a long-term survival approach [26, 27]. Since diversity is a fundamental aspect of energy security, a focus on the vulnerability potentially contained in a vital energy system based on the combination between of its exposure to risks and diversity should be a starting point of quantitative study of energy security by using the vulnerability-based approach.

In addition, among various forms of vital energy systems proposed in the vulnerability-based approach, this study focuses on electricity system. In last three decades, the electricity consumption has increased by 150% and the share of electricity in total final energy consumption has increased by 50% [28]. Electricity security, or energy security dedicated for electricity, is vital to wellfunctioning modern societies. It is expected that it will become more importance throughout the increase in the share of electric vehicles and the improvement of electrification rate in developing countries.

Among several aspects associated with diversity in the vital electricity system, diversity in power mix has been widely used as an important indicator in the global energy policies [21, 29]. For example, the World Energy Council (WEC) issues diversity in power mix based on Shanon-Wiener index (SWI) [30] and the World Economic Forum (WEF) issues diversity of total primary energy supply based on Herfindahl-Hirshman index (HHI) [31]. Diversity in power mix acts to moderate the vulnerability of an electricity system against the disruption of continuous energy supply caused by an interruption of a single electricity supply source [32, 33]. Notably, an interruption of electricity supply source corresponds to risk to which the electricity system is exposed in this study. Especially in the electricity sector, improvement of diversity in power mix through use of various generation sources and technologies can largely contribute to enhancement of energy security, technological competitiveness, and sustainability [34, 35]. Considering the lack of quantitative study of energy security under the vulnerability-based approach, the quantitative approach for diversity in power mix will be further explained from the perspective of risk.

According to Cherp and Jewell, risk to which the electricity system has two natures: shocks and stresses. These natures originate from the concept of "change" defined by Stirling. He called what threatens the energy system as "change", which is categorized into two types; e.g. episodic shocks and secular stresses [36]. Stresses are long-term and static change under the steady state, while shocks are short-term and dynamic change under the non-steady state. Notably, the span considered in the energy security narrative of long-term secular stresses would be decades under the lifecycle notion. The diversity in the long-term energy security (stress) has been conventionally evaluated by accounting for energy generation of each power component in a certain time-scale range (e.g., one year at most). The term of "sudden" in sudden external interruptions causing a dynamic change of electricity system, which is discussed in the short-term energy security narratives, corresponds to a given instant of time series when short-term episodic shocks happen, lasting for minutes to weeks [37]. Such changes potentially cause the risk that an electricity supply source is interrupted. Therefore, the vulnerability of electricity system dedicated for each power source in terms of supply interruption needs to be addressed in the quantitative assessment based on the nature of risk including both stresses and shocks.

It must be noted that diversity in power mix has been conventionally considered as a factor in the long-term energy security for securing continuous energy supply in the future [8, 21, 38]. Thus, based on long-term secular stresses, diversity in power mix has been expressed in terms of the degree of reliance on each energy source for the continuous energy supply [39] and this reliance links to static vulnerability in this study. Such reliance has been derived from the share of energy source in total primary energy supply and power generation [40, 41, 42, 43, 44]. This stresses-based approach for evaluating diversity in power mix in the quantitative manner has been widely used in the national policy measures and energy security study under the dimension-based approach.

On the other hand, although shocks are theoretically and qualitatively relevant to diversity in power mix, dynamic vulnerability [12, 15, 29, 45], a combination of exposure to shocks and diversity, has hardly been evaluated in a quantitative manner. Stressed-based approach of accounting energy generation only through a long-term scope could potentially result in a short-sighted understanding on diversity in power mix in energy security. Although diversity is considered as a factor in the long-term energy security as mentioned above, it is essential that short-term sudden supply interruptions are addressed in diversity as well [22]. Since each of energy sources in the energy system is associated with different characteristics and risks of energy disruption in different time scale, energy generation alone does not simply correspond to the vulnerability of power system to interruption of power source [46]. In this context, Kisel et al. highlighted that the long-term energy security issues can potentially lead to short-term operations of energy security, and vice versa [29].

Considering the significant interaction between long-term and short-term energy security, this study aims to take more comprehensive approach for in-depth understanding of diversity in power mix through investigating the vulnerability of electricity system to interruption of electricity supply source from the perspective of both stresses and shocks.

1.2 Research objective and questions

While aspects of diversity in power mix have been widely studied in detail by a wide range of scholars accounting for energy generation by power sources as static vulnerability based on stresses, this study aims to fill the gap in the studies regarding the dynamic vulnerability of an electricity system against the disruption of continuous electricity supply caused by sudden disturbances on an electricity supply under the notion of shocks.

Objective of this research

The objective of this study is

1. To conceptualize the dynamic vulnerability
2. To develop the methodology for its quantification
3. To analyze the static and dynamic vulnerability of vital electricity system in the context of diversity in power mix.

Research questions

The central research question for this study is: **what is the difference of trend between static and dynamic vulnerability in the context of diversity in power mix in energy security?** This question would be further broken down into the related sub-questions to accomplish the objective of the thesis as follow:

There are multiple threats to the security of energy and electricity supply [17]. Among the various attributes in threats, the impact of each threat on the energy system could be categorized into two types; e.g. short-term episodic shocks and long-term secular stresses [36]. Although diversity in power mix has been considered as a factor in the long-term energy security, the relationship between short-term episodic shocks and diversity in fuels has been theoretically highlighted on a conceptual basis [47]. In most of the policy making and design, attentions were focused to short-term energy security, in which sudden disturbances on power system under emergency conditions are of major concerns [48]. To compare the trend between static and dynamic vulnerability in the context of diversity in fuels, this study needs to identify the boundary of electricity system in the assessment of static and dynamic vulnerability and the fundamental concept behind the dynamic vulnerability.

Based on this background, I may say that the questions one should ask for the well-understanding of diversity would be:

Sub-Q1: "What is the concept of dynamic vulnerability proposed in this study?"

The number of existing indicators which can be used for the assessment of short-term energy security are limited, compared with long-term energy security. Among a limited number of indicators for short-term energy security, WEC monitors the ratio of energy production to consumption and WEF measures the quality of electricity supply by using specific indicators [29]. Although each indicator focuses on a specific feature in short-term energy security, they do not sufficiently cover the concept of dynamic vulnerability assessed in this study. For example, these existing indicators present the outcomes based on past experience, barely taking into consideration the vulnerability potentially contained in the electricity system corresponding to each power source under the time-series notion. Therefore, the quantified method and index dedicated for the dynamic vulnerability in the context of diversity in power mix is newly required to be finally applied to short-term energy security study.

Based on this background, I may say that the questions one should ask would be:

Sub-Q2: "How can the dynamic vulnerability be quantified in the context of diversity in power mix?"

And then,

Sub-Q3: "What index dedicated for the dynamic vulnerability should be developed?"

Diversity in power mix has contributed to design of the electricity system and determination of the capacity sizing. In the dimensioned-based approach for the analysis of national energy security, energy generation by power source as static vulnerability in a national scale of electricity system was accounted for to be applied into determination of capacity size. Additionally, in the process of determining capacity size in the distributed system, several authors predeclared that "*This research likewise only deal with static vulnerability*" in their studies (e.g., [49, 50, 51, 52]). Meanwhile, most of research studies have not even mentioned any limit of reliability concepts, and dynamic vulnerability is simply dimmed out from their assessments for determining capacity size. Therefore, the applicability of developed index into a given electricity system needs to be demonstrated for the comparison of static and dynamic vulnerability.

Based on this background, I may say that the questions one should ask would be:

Sub-Q4: "How can the developed index dedicated for dynamic vulnerability be applied?"

These sub-questions dedicated for dynamic vulnerability will be answered by conceptualizing the dynamic vulnerability in the context of diversity in power mix, and developing the methodology of assessing the dynamic vulnerability of the electricity system to the disruption of continuous power supply arising from a sudden disturbance on a single energy source. Finally, the difference between the static vulnerability conventionally developed and the dynamic vulnerability newly addressed in this thesis (corresponding to 4 sub-questions) will be analyzed to address the central question.

The overview of research questions is presented in Figure 1.1.

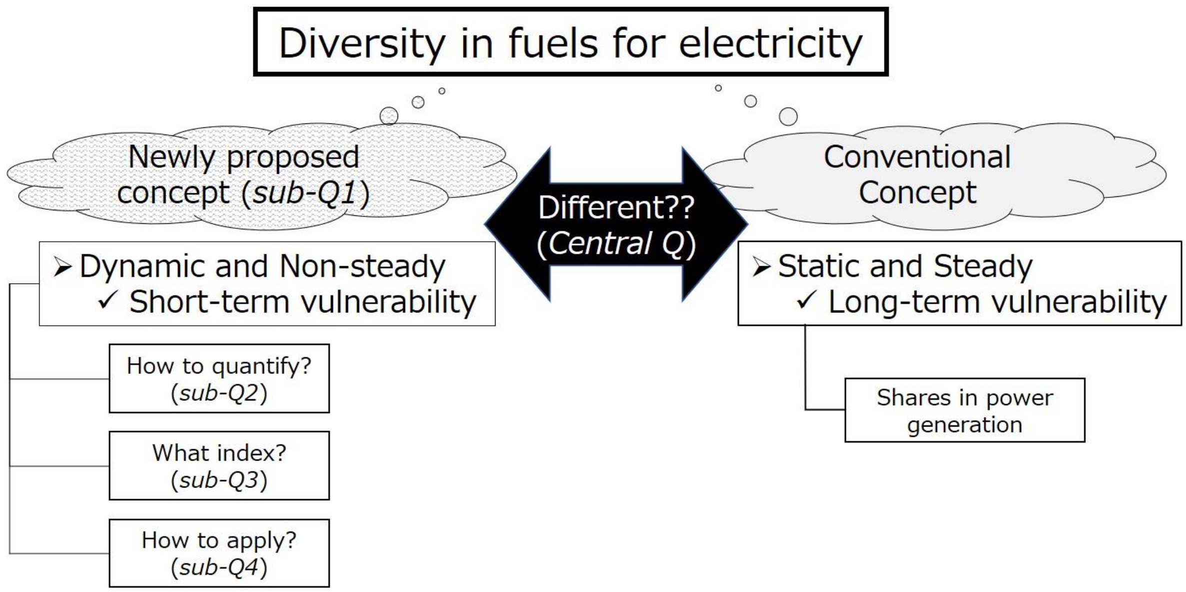

Figure 1.1 Overview of research questions

1.3 Structure of the thesis

This thesis is structured as follows:

In Chapter 2, a comprehensive literature review on existing energy security studies is conducted. Given that the diversity in power mix from the short-term perspective has scarcely been addressed, the literature review on short-term energy security is first presented. Subsequently, the existing studies working on the reliability assessment is reviewed, particularly in the hybrid renewable energy system. Finally, the research gap and potentials in applications of dynamic vulnerability assessment are discussed.

In Chapter 3, study on conceptualization of the static and dynamic vulnerability in the context of diversity in power mix is conducted. Based on the developed concept, a particular method for analyzing the dynamic vulnerability of the electricity system considering the occurrence of sudden disturbances on a power source is developed. The three major components are introduced, that is: magnitude, duration and instant of failure.

In Chapter 4, the assessment of dynamic vulnerability in the fictious centralized power network is conducted on the basis of the developed methodology by specifically taking into account the sudden disturbances on nuclear energy use. A new index dedicated for the dynamic vulnerability of electricity system considering the interruption of nuclear power utilization, named System Interruption Nuclear Vulnerability Index (SINVI) is developed. Finally, the relationship between the SINVI based on dynamic vulnerability, the diversity in power mix based on static vulnerability, and the redundancy based on the short-term energy security is analyzed to design the more secured power system taking into account the risk of nuclear energy utilization.

In Chapter 5, the assessment of dynamic vulnerability in the fictious distributed power network is conducted on the basis of the developed methodology by taking into account the sudden disturbances on both the renewable energy and storage technology. Then, a new index to quantitatively measure dynamic vulnerability is developed. Based on the developed index and cost, the process of determining capacity sizing is demonstrated by employing additive aggregation approach and data envelopment approach.

In Chapter 6, the static and dynamic vulnerability in the fictitious centralized and distributed power network is compared and discussed. The different degree of vulnerability by each of power sources in the context of diversity in power mix is identified by extending and integrating Chapter 4 and Chapter 5. Then, the implication from the obtained results is extracted and the limitation of this study is discussed by interpreting the concept of diversity.

Chapter 7 concludes the thesis.

Table 1.1 relates the research questions to the relevant chapters in this study. The structure of the argument used to address the research questions posed in the study is depicted in Figure 1.2.

Table 1.1 Research questions and organization of the thesis

Research question		Primarily addressed in:
Sub-research questions		
Q1	What is the concept of dynamic vulnerability proposed in this study?	Chapter 3.1
Q2	How can the dynamic vulnerability be quantified in the context of diversity in power mix?	Chapter 3.2
Q3	What index dedicated for the dynamic vulnerability should be developed?	Chapter 4, Chapter 5
Q4	How can the developed index dedicated for dynamic vulnerability be applied?	Chapter 4, Chapter 5
Central research question:		
	what is the difference of trend between static and dynamic vulnerability in the context of diversity in power mix in energy security?	Chapter 6, Chapter 7

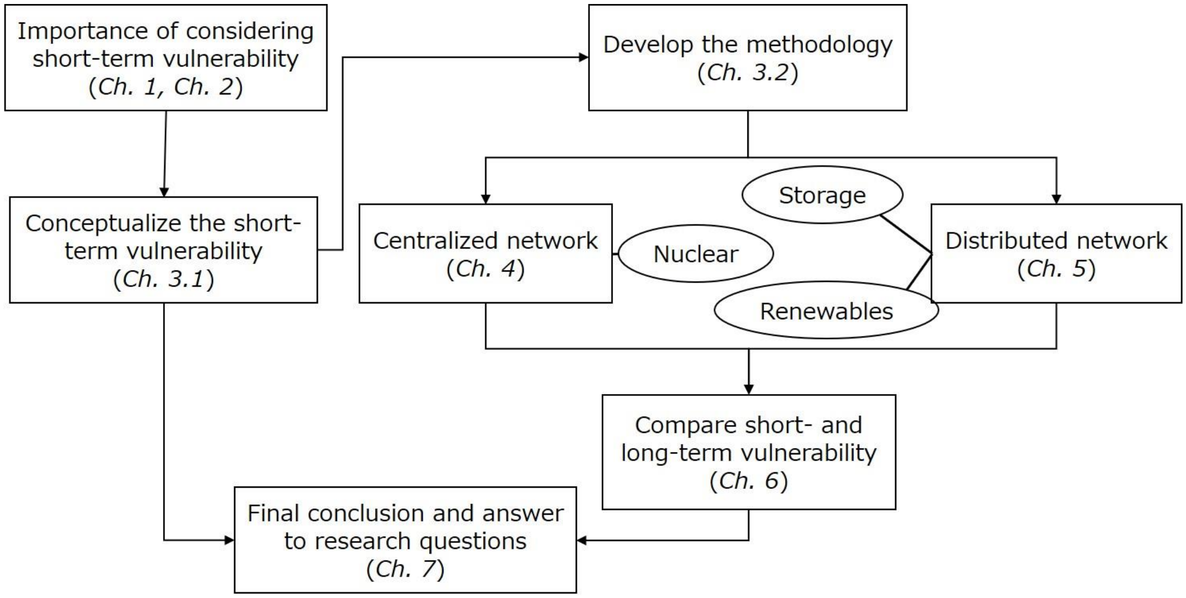

Figure 1.2 Logic diagram of the structure of the study

CHAPTER 2 : LITERATURE REVIEW

2.1 Short-term energy security

Given that the diversity in power mix from the short-term perspective has scarcely been addressed, this Section primarily aim to outline the literature review on short-term energy security.

There are multiple threats to the security of energy and electricity supply [17]. Among the various attributes in threats, the impact of each threat on the energy system could be described in the time-scale form [5]. Stirling called what threatens the energy system as "change", which is categorized into two types; e.g. short-term episodic shocks and long-term secular stresses [36]. This notion could be also found in the work of Stern [53], where shocks and stresses are described as "short-term" and "long-term" impacts. Batlle et al. presented a two time-scale characteristics in the electricity security: e.g. the long-term electricity security which is an ability of installed capacity to meet demand, and the short-term electricity security which is an ability of electricity system to withstand a sudden disturbance [45]. In other words, diversity in power mix addresses the secular stresses under the long-term and steady condition based on static vulnerability and the episodic shock under the short-term and non-steady condition based on dynamic vulnerability.

In most of the policy making and design process, attentions were mostly focused to short-term energy security in which sudden disturbances on energy system under emergency situation are the major concerns [48]. Particularly in the power system, the challenge is to ensure a rapid and adequate response of the system after sudden disturbances to avoid critical vulnerabilities of supply security without fundamental change under an intelligent control and high flexibility of existing capacities [37, 54]. In this context, Kisel et al. summarized the short-term energy security as operational and technical resilience in the electricity sector and identified its importance for energy policy design [29].

Although diversity in power mix is considered as a factor in the long-term energy security, the relationship between short-term sudden disturbances and diversity in power mix has been theoretically highlighted on a conceptual basis [47]. Yergin stated that diversity contributes to improving the ability of energy system to respond short-term shocks [22]. In terms of fuel type, Chuang and Ma highlighted that diversity in power source reduces the vulnerability of energy supply disruption caused by a sudden loss of a single power source [39]. Even in ecology, more diversified system is advantageous for recovering from sudden disturbances and returning to its stable state in a faster manner [55]. Sovacool also introduced a potential effect of diversity on minimizing the damage of malicious attacks and natural disasters [10], which are also considered as sudden disturbances as previously mentioned.

Based on the review of these previous works, we may argue that the major questions to further understand the concept of diversity in power mix would be "how can the dynamic vulnerability be quantified in the context of diversity in power mix? (sub-Q.2)" and "What index dedicated for the dynamic vulnerability should be developed? (sub-Q.3)".

The number of existing indicators which can be used for the assessment of short-term energy security are limited, compared with long-term energy security. Among a limited number of indicators for short-term energy security, the WEC monitors the ratio of energy production to consumption and the WEF measures the quality of electricity supply by using specific indicators [29]. Although each indicator focuses on a specific feature in short-term energy security, they do not sufficiently cover the concept of dynamic vulnerability assessed in this study. For example, these existing indicators present the outcomes based on past experience, barely taking into consideration the vulnerability potentially contained in the electricity system corresponding to each power source under the time-series notion.

2.2 Reliability analysis

The vulnerability of an electricity system against the disruption of continuous energy supply caused by an interruption of a single electricity supply source from the short- and long-term perspective in the context of diversity in power mix would be highly associated with the concept of "reliability" in the power system [56].

Conventionally, the wide range and multiple layer structure of hierarchical levels (HL) including the generators, transmission and distribution lines, transformers and power load are the major constituent of power system and these constituents are linked in series, parallel and meshed [57]. Recently, owning to the community-based nature of renewable energy, the concept of local production for local consumption has been highlighted. The incremental diffusion of renewable energy requires the transition of grid style from centralization to decentralization. Moreover, market liberalization and two-way informational communication would significantly entangle the modern power system and alter its dynamic behavior [49]. Given the complicated modern power system network, the improvement of system reliability is of paramount importance to ensure the continuous power supply.

In the power system narratives, Allan defined reliability as the measurement of power system ability to meet the electricity demand of end-users [58]. Power system reliability is expressed in the form of various indices [59]. The widely accepted reliability indices include Loss of power supply probability (LPSP) [60, 61, 62, 63, 64, 65, 66, 67, 68, 69], defined as the ratio of summation of energy deficit over the total energy demand during the considered period, Loss of load expectation (LOLE) [70, 71], defined as the ratio of summation of energy deficit duration over the considered period, Loss of load probability (LOLP) [72, 73, 74, 75, 76, 77, 78], defined as the probability of supplied power not meeting the demand for the considered period, and Expected energy not supplied (EENS) [79], defined as expected energy deficiency when the demand is greater over the supply. The different indices for reliability evaluation have been also proposed in various studies, including deficiency of power supply probability [80], system autonomy [76], percentage of risk and healthy state probability [81], max energy not supplied [82], and loss of load hours [67].

Evaluation of reliability is useful for the planning and operation of power system and designing the capacity size in the power system by integrating reliability with the different multiple indicators such as economic and environmental [57]. Various economic indicators have been proposed including total annualized cost of system [83], levelized cost of energy [60], system to total cost [84], net present value [85], while carbon dioxide emissions are often computed to represent the environmental indicator [86, 87, 88]. These multiple indicators are aggregated by employing various optimization techniques to determine the best system capacity including non-linear programming techniques [89, 90], genetic algorithm [83], particle swarm optimization [91], evolutionary algorithm [92] and others. Detail descriptions of optimization techniques in the power system are presented in the review studies [93, 94, 95].

Notwithstanding the significant contribution of reliability application to the planning and designing, reliability has yet to be fully evaluated in the existing studies. Power system reliability is fundamentally developed on a basis of two concepts: adequacy and security [96, 97, 98]. System adequacy is considered as a static reliability, which estimates the power system ability to provide electricity to customers within a determined specific standard for a long term, while system security is considered as a dynamic reliability, which correlates with the power system ability to overcome the sudden disruptions of constituents for a short term [99, 100]. It must be mentioned that almost all reliability research works have only focused on the system adequacy under the static, long-term and steady state. Several authors predeclared that "*This research likewise only deal with power* *adequacy aspect*" in their studies (e.g., [49, 50, 51, 52]). Meanwhile, most of research studies have not even mentioned any limit of reliability concepts, and system security is simply dimmed out from their reliability assessments. However, it is obvious that the exclusion of system security results in the overlook of essential dimension in the comprehensive notion of reliability assessments since power system is potentially affected by unpredictable and unavoidable sudden transient failures and disturbances [101]. Multiple types of technical contingencies occur due to the vulnerabilities of natural disasters and human errors [102]. In addition, difficulties of power flow control at the interconnection between transmission lines and microgrids have raised the risk of sudden power outages [103]. The detailed review of reliability assessment is presented in Appendix.

2.3 Discussion

Reliability assessment for its application to determining capacity size in the electricity system highlighted in Chapter 2.3 is highly relevant to diversity in power mix in the energy security narrative. Particularly, considering the concept of each technical term, system adequacy and system security in the reliability narrative corresponds to static vulnerability and dynamic vulnerability in the context of diversity in power mix. System adequacy of power supply in the reliability narrative is highly associated with static vulnerability in the context of diversity in power mix as a factor of long-term energy security. This is because both concepts accounts for energy generation under the long-term and static condition, and the same methodological concept (Accounting the share of energy generation amount by each power source) is applied. The intermittent electricity generated by renewable energy is considered in this static condition. The system security of power supply in the reliability narrative focuses on the system adapting ability to meet the power demand even after the sudden occurrence of external disturbances under the short-term and dynamic condition, and this concept matches the notion in the dynamic vulnerability in the context of diversity in power mix based on short-term operations of energy security. Although the system security in the reliability narrative is based upon the short-term energy security, there is no specific index dedicated for measuring its ability to withstand the sudden disturbances on energy sources. As dynamic vulnerability has hardly been evaluated in the context of diversity in power mix, the system security has scarcely been incorporated in the reliability assessment for determining capacity size.

Although there are various common indices for static and dynamic reliability assessment, the quantification method of system security has the complexities and high cost of computational model and simulation [104], the difficulties of developing theoretical concepts and criterions [51], and insufficient available data [105]. These shortcomings might be because of the wide range of hierarchical levels of power system category inevitably assessed in the system security.

Here, the main purpose of this study is to quantify the short-term diversity in the context of diversity in power mix. Since diversity in power mix needs to focus on the dynamic vulnerability dedicated for each of power source, the stage of transmission and distribution in the hierarchical levels can be out of scope. In other words, the assessment of system security can limit the scope of categories into the balance between the generation facilities and load, as the adequacy assessment does. The reduction of target scopes would contribute to overcoming the aforementioned difficulties in application of system security to determination of capacity size.

CHAPTER 3 : Conceptualization and methodology

3.1 Boundary of diversity in power mix

Fuel use for electricity is divided into four stages, e.g. procurement of primary energy resources, power generation at facilities, transmission and distribution. In the context of overall electricity security, the whole stages need to be considered [106], whilst analysis on diversity in fuel is conducted in the stage of primary energy resource procurements and power generation at facilities, where distinction of fuel type for electricity is clearly recognized.

Procurement of primary energy resource has been conventionally considered as a factor of long-term energy security, where stresses, such as environmental impacts, depletion of energy resource, political instability and rapid growth of energy demand, are involved to cause the static vulnerability of energy system [5]. On the other hand, the risk in the stage of power generation at facilities could be closely related to short-term energy security. Various types of sudden disturbances could potentially occur at facility bases under HL-1, and those disturbances include technical and human failures (e.g., insufficient maintenance) [101], natural disasters (e.g., earthquake) [102], societal issues (e.g., stoppage of nuclear facility due to lawsuits) and malicious events (e.g., cyber-attack and terrorism) [107]. In practice, Sovacool also considered facility-related issues as indicators of diversification [10], which means that the generation facilities are highly relevant to the concept of diversity in power system. Such disturbances at power generation facilities under HL-1 consequently cause sudden loss of generation capacity.

The importance of diversity in power mix under HL-1 for moderating the dynamic vulnerability has been highlighted from some past experiences. For examples, Hokkaido in Japan experienced a massive blackout due to the earthquake in 2018. After the earthquake occurred, coal power plants, which had contributed to more than half of electricity demand in Hokkaido shut down, leading to a significant loss of power generation capacity. Such a loss caused damage to the technical control of transmission and distribution under HL-2 and HL-3, and then the hydro power plant of 43MW and the wind power plant of 17MW were interrupted. The cascading power outages cause a disastrous variety of indirect and direct losses in the human economy and society [108]. High reliance on coal power capacity triggered off a disruption of power supply. In addition, the governmental strategy and social pressures on decision of power energy sources would apparently trigger the compelling sudden shutdown of power plants and extensive national outages. In the aftermath of Fukushima nuclear accident in 2011, Japanese government stopped the operation of all nuclear power plants, which had previously contributed approximately 30 % of the electricity supply, due to safety re-inspection and conducted the planned power cut, which caused the significant drop of supply capability and deteriorated the dynamic vulnerability in the electricity system [109, 110]. The issues of lawsuits for demanding injunction of nuclear power reoperation from anti-nuclear power public movements [111] and the prior notice of nuclear terrorism [112] would consequently beget power outages [113]. Besides the case where end-users experience the loss of accessibility to electricity supply, there are many incidents of sudden loss of power generation which do not affect the demand pattern of end-users. For example, 19 unpredicted disturbances under HL-1 were recorded in Japan in May, 2020 [114].

There are notable risks of sudden disturbances during the procurement of primary energy sources, such as military tension at the maritime chokepoint and malicious attacks on the transport infrastructure [115]. Many countries adopt strategies of securing their fossil fuel stockpile to cope with such risk of sudden import stoppage; for instance, stockpiles of oil and natural gas are secured in a national sector for 90 days and 50 days, respectively in Japan. Considering these strategies, the stoppage of import is categorized in the long-term energy security issues [116] and not as a short-term energy security in this study.

Therefore, it could be generally said that the static vulnerability is relevant to the stage of primary energy resource procurement, whereas the dynamic vulnerability is relevant to the stage of power generation at facilities. As the summary of the discussions above, the overview in the boundary of static and dynamic vulnerability in the context of diversity in power mix adopted in this study is presented in Figure 3.1.

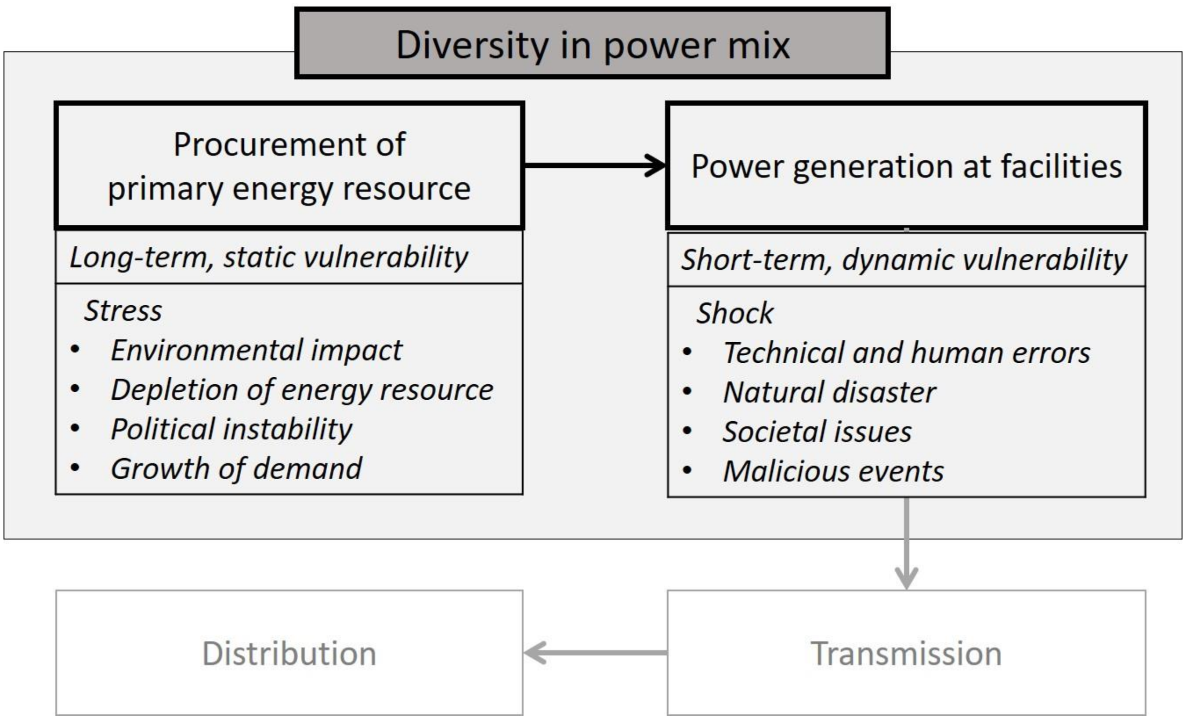

Figure 3.1 Boundary of static and dynamic vulnerability in the context of diversity in power mix

3.2 Conceptualizing the dynamic vulnerability

The main part of the analysis in this study corresponds to the evaluation of dynamic vulnerability in the stage of power generation at facilities for sudden disturbances which is a key component of the diversity in power mix. Here, we focus on the vulnerability of the electricity system under an interruption of one of the power sources to evaluate the diversity in power mix. Diversity in power mis has been conventionally examined on the basis of static vulnerability by accounting for the share of energy generation by each power supply source. Similar to the system adequacy assessment in the power system narrative, sufficiency of power generation to meet demand is fundamental to the static vulnerability in the context of diversity in power mix. Considering that one of the objectives in this study is to analyze the difference of the trend between static and dynamic vulnerability, it is required that the methodology for assessing the dynamic vulnerability of the electricity system to the disruption of continuous power supply arising from a sudden disturbance at the facilities on a single energy source is likewise developed on the basis of the concept of sufficiency of power generation to meet demand.

Electricity reliability reflects the fundamental aspect of the ability of the power system to withstand sudden interruption of system components [96, 117]. This study interprets its ability as the degree of sufficiency of power generation to meet demand. In other words, the dynamic vulnerability depends on whether the system maintains supply capability to generate sufficient power for meeting demand even after an occurrence of sudden interruption of electricity supply source. The system which maintain the minimum supply capability can remain self-sufficient. Since the supply capability is fundamental to sufficiency, technical features including rotor angle, frequency and voltage in the narrative of power system engineering is out of focus.

The methodology for evaluating short-term diversity in the context of diversity in power mix needs to cover the several characteristics including sufficiency, a focus on the generation stage under HL-1, vulnerability potentially contained in the system, a focus on each power source, and consideration of time-series notion. There are limited indices dedicated for short-term energy security such as reliability indices (System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), System Average Interruption Frequency Index (SAIFI) and Customer Average Interruption Frequency Index (CAIFI)), fuel stockpile, and power capacity margin. Although each indicator focuses on a specific feature in short-term energy security, they do not sufficiently cover the concept of dynamic vulnerability assessed in this study. For example, these existing indicators present the outcomes based on past experience, barely taking into consideration the vulnerability potentially contained in the electricity system corresponding to each power source under the time-series notion. The relationship between the necessary characteristics and existing short-term energy security indices is summarized in Table 3.1. Therefore, the quantified method and index dedicated for the dynamic vulnerability in the context of diversity in power mix is newly required to be finally applied to short-term energy security study.

It must be noted that the assessed duration in the short-term energy security varies depending on the aforementioned indicators. For instance, power capacity margin is basically assessed within a day, while fuel stockpile is for 2-3 months. Particularly, SAIDI is monitored during a year, which is basically the same as the duration assessed in the diversity in power mix on the basis of static vulnerability. In spite of difference in the monitored duration, such indicators for the short-term energy security commonly express the dynamic vulnerability potentially caused by sudden interruptions. As such, this paper considers the short-term behavior as the dynamic change of balance between demand and supply caused by sudden disturbances within a certain duration.

Table 3.1 Characteristics of existing short-term energy security indices

Characteristics	SAIDI	Fuel stockpile	Power capacity margin
Sufficiency	×	○	○
Dedicated for the generation stage (HL-1)	△	×	○
Addressing vulnerability potentially contained in the system	×	△	○
Dedicated for each power source	×	△	×
Considering the time-series notion	△	△	△

This study determines the scale of sudden disturbances based on the magnitude and duration of disturbances on facilities for power generation at an arbitrary time. There would be a threshold of magnitude and duration of disturbances that the power system can maintain the continuous power supply in a self-sufficient manner. Its threshold indicates the dynamic vulnerability of power system; the greater threshold corresponds to the lower dynamic vulnerability of power system to supply disruptions due to sudden disturbances.

The concept of failures in a given power supply source needs structuring based on the three factors: failure rate, failure duration and instant of failure. These are defined as follows:

1. Failure rate refers to the percentage of failure. It is a measured as a magnitude.
2. Failure duration represents the period that a failure of energy source lasts. It is measured in a time scale.
3. Instant of failure stands for the time when the failure occurs. It is a specific time.

These three factors represented graphically in Figure 3.2 are considered major parameters for evaluation of the dynamic vulnerability of the power system. Failure rate is 0% when the energy source is fully capable, and it rises to 100% if the power source fails. With the sudden occurrence of the failure the rate is instantly increased, remaining at the same level until recovery. Failure duration is in practice considered from minutes to months (2-3 months would be maximum according to fuel stockpile), failure duration in this research is less than 24 hours in order to limit the time scale up to one day after sudden disruption. The model is simulated by changing the three major parameters described above. It is assumed that the power demand is not affected by sudden disturbances since this study focuses on the ability of the system can maintain the supply capability and remain self-sufficient. As mentioned above, there are many incidents of sudden loss of power generation in cases where end-users do not experience the loss of accessibility to electricity supply. Even if sudden disturbances affect the demand pattern of end-users, the demand is expected to decrease under the emergence. As such, such assumption would be considered as a worst case in terms of balance between demand and supply.

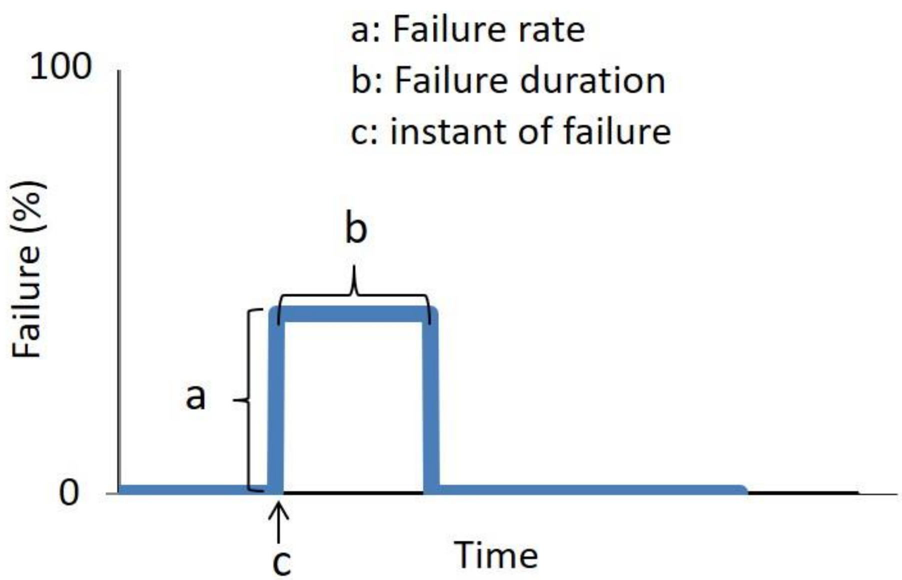

Figure 3.2 Concept of sudden disturbances on energy source

3.3 Quantification approach for the dynamic vulnerability

As outlined previously, failure rate, failure duration, and instant of failure in the system are the constituent parameters for evaluation of dynamic vulnerability in this study. Particularly, both the maximum failure rate and the maximum failure duration corresponding to the different instant of failure determine the ability of power system to remain self-sufficient. As an initial step variation in such parameters must be represented in order to generate the proposed indices of dynamic vulnerability.

The first relationship represented is that between failure duration and instant of failure evaluated at different failure rates. In this case, the focus is on the time duration when the power system remains self-sufficient. This relationship expressed graphically is known as the DI curve. Such curve is obtained by changing the parameters in the steps described below, presented in Figure 3.3.

1) Initial setting of parameters: *failure rate* = 100%, *failure duration* = 1 min, *instant of failure* = 00:00 hrs.

2) Start of simulation and energy deficit verification. In this assessment, the energy deficit is defined as the total lack of power supply to the meet the demand in 24 hr.

3) For NO energy deficit observed, *failure duration* is increased in 1 min steps. Model simulation is repeated until energy deficit appears.

4) For energy deficit observed, the previous *failure duration* is set as the maximum accepted *failure duration* corresponding to the simulated *failure rate* and *instant of failure*.

5) Step 2), 3) and 4) are repeated increasing the *instant of failure* from 00:01 until 24:00 by its corresponding step.

6) Step 2), 3), 4) and 5) are repeated decreasing the *failure rate* until 0 % by s %.

7) Obtained results are plotted on a 2-axis graph of *failure duration* versus *instant of failure* in curves representing *failure rate*.

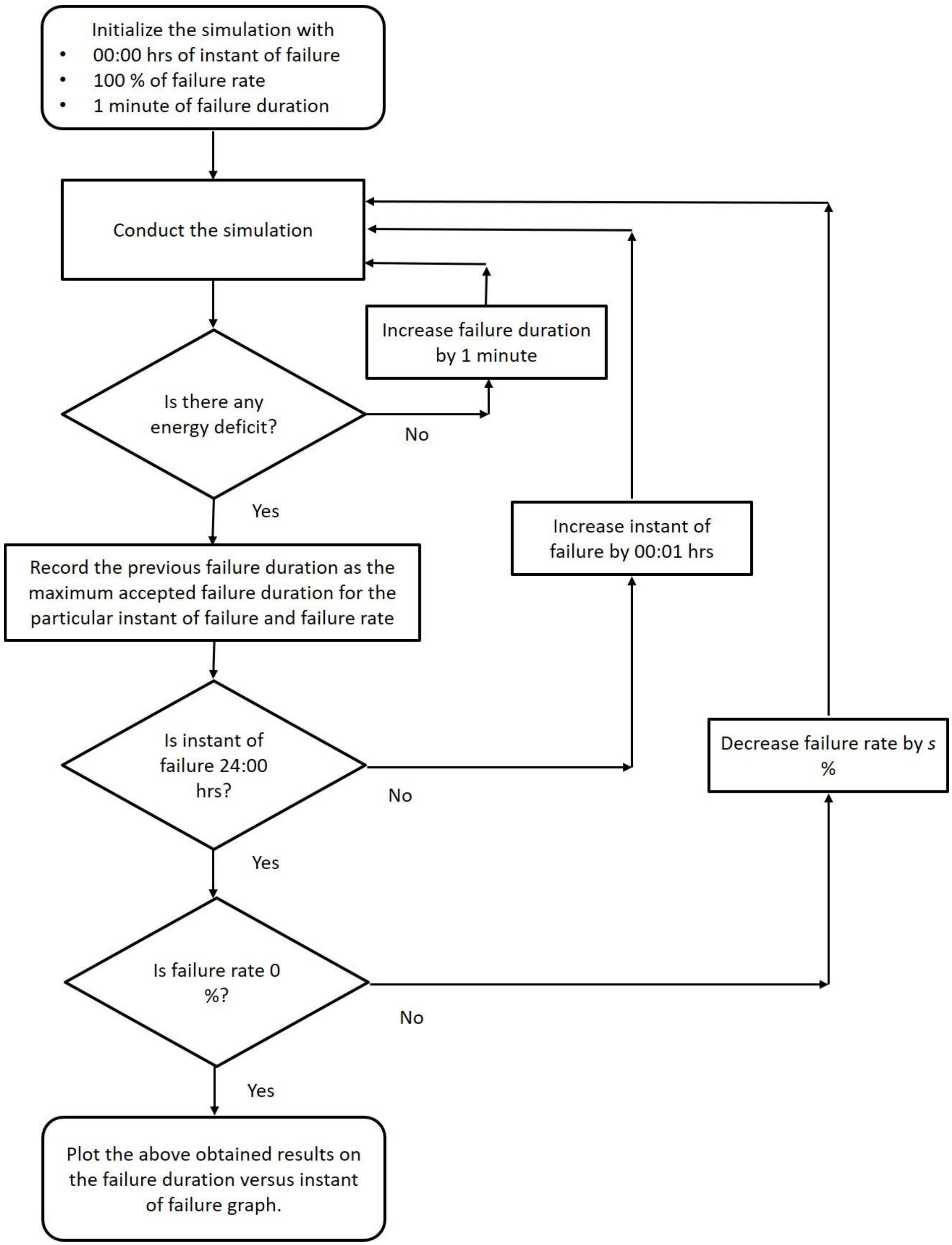

Figure 3.3 Flowchart of the steps for obtaining the DI curve

The second relationship under study is that between failure rate and instant of failure at different failure duration. In this case, the focus is on the failure rate at which the power system remains self-sufficient. This relationship expressed graphically is known as the RI curve. Such curve is obtained by changing the parameters as described below, presented in Figure 3.4.

1) Initial setting of parameters: *failure rate* = 0%, *failure duration* = t hr, *instant of failure* = 00:00 hrs.
2) Start of simulation and energy deficit verification.
3) For NO energy deficit observed, *failure rate* is increased in steps of 1%. Model simulation is repeated until energy deficit appears.
4) For energy deficit observed, the previous *failure rate* is set as the maximum accepted *failure rate* corresponding to the simulated *failure duration* and *instant of failure*.
5) Step 2), 3) and 4) are repeated increasing the *instant of failure* from 00:01 until 24:00 by its corresponding step.
6) Step 2), 3), 4) and 5) are repeated increasing the *failure duration* until 24 hr by t hr.
7) Obtained results are plotted on a 2-axis graph of *failure rate* versus *instant of failure* in curves representing *failure duration*.

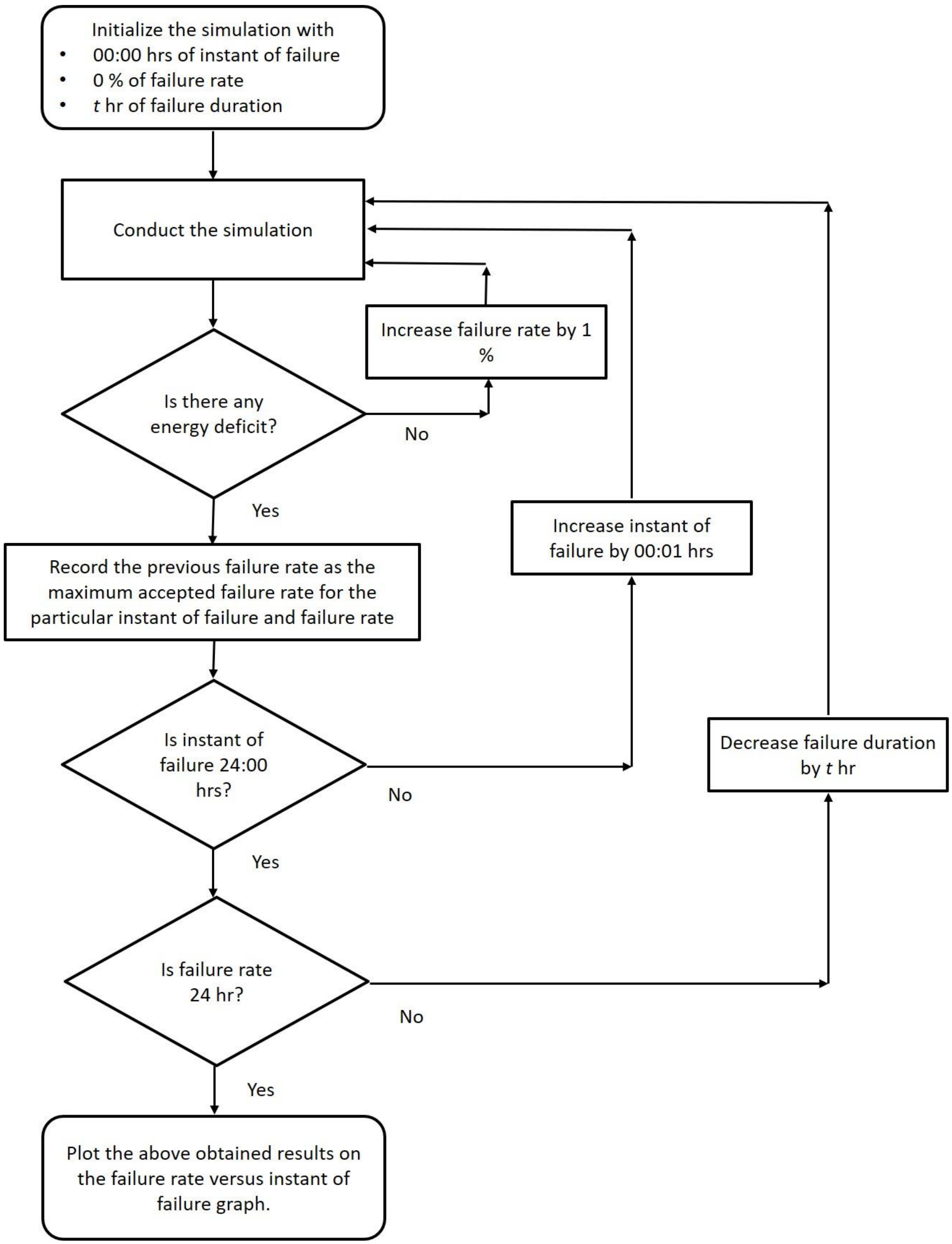

Figure 3.4 Flowchart of the steps for obtaining the RI curve

The third relationship under study is that between failure rate and failure duration at different instant of failure. The threshold of failure rate and duration at an arbitrary instant of time in each of power sources is evaluated. The threshold is on the most critical failure rate tolerable in the power system corresponding to a specific failure duration, or as a reverse interpretation the longest failure duration tolerable in the power system corresponding to a specific failure rate. This relationship expressed graphically is known as the DR curve. Such curve is obtained by changing the parameters as described below, presented in Figure 3.5.

1) Initial setting of parameters: *failure rate* = 1%, *failure duration* = 1 min, *instant of time* = 00:00 hrs.
2) Start of simulation and energy deficit verification.
3) For NO energy deficit observed, *failure rate* is increased in steps of *x* %. Model simulation is repeated until energy deficit appears.
4) For energy deficit observed, the previous *failure rate* is recorded in the simulated condition of *failure duration* and instant of failure.
5) Step 2), 3) and 4) are repeated increasing the failure duration from 1 min until 24 hr by *y* min.
6) Step 2), 3), 4) and 5) are repeated increasing the instant of time until 24:00 hrs by its corresponding step.
7) Obtained results are plotted on a 2-axis graph of failure rate versus failure duration in curves representing instant of time under the selected power source component.

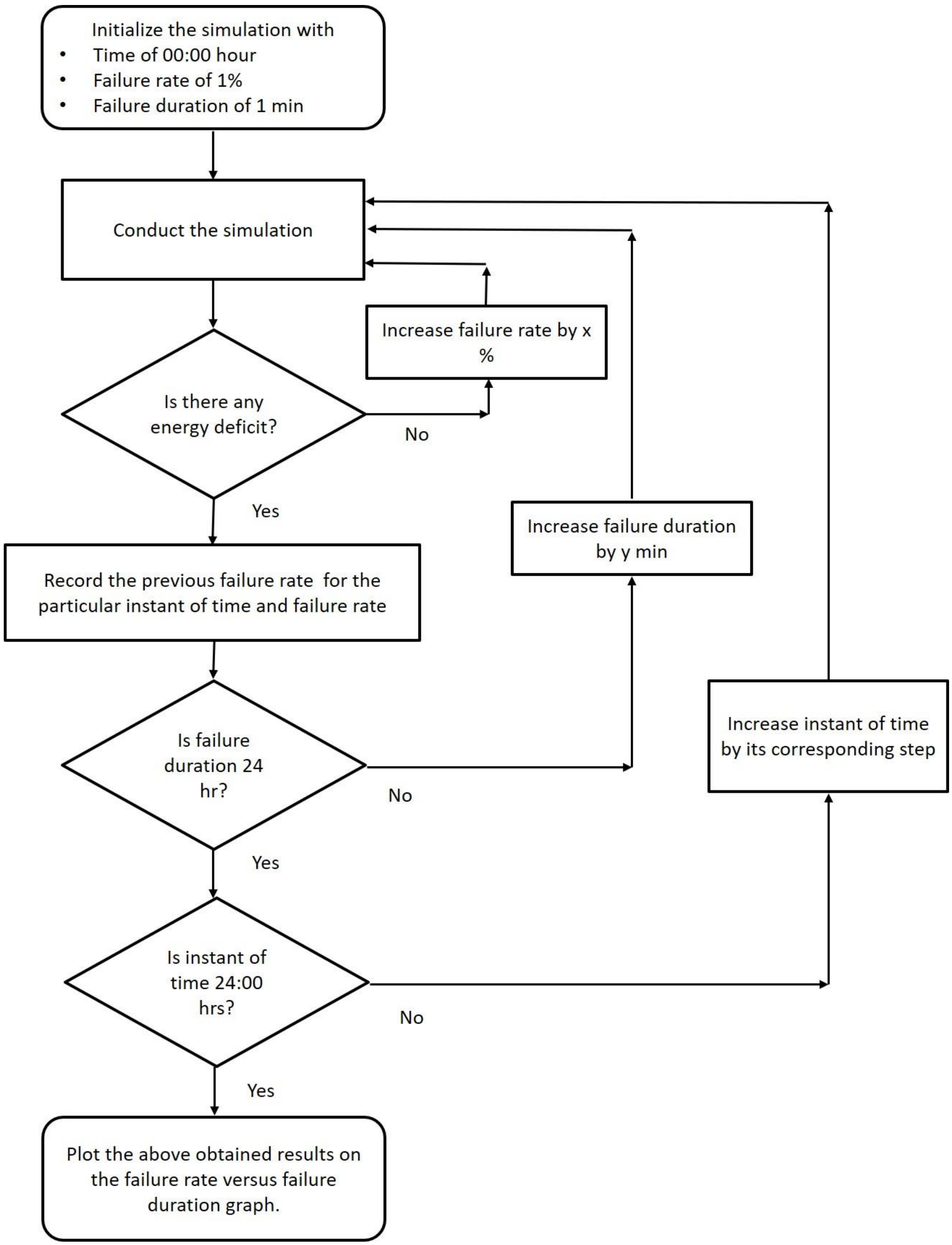

Figure 3.5 Flowchart of the steps for obtaining the DR curve

In this Chapter, the dynamic vulnerability in the context of diversity in power mix has been conceptualized. Its core is that the dynamic vulnerability depends on whether the system maintains supply capability to generate sufficient power for meeting demand and remains self-sufficient without any reliance on power supply from other systems even after an occurrence of sudden interruption of electricity supply source. Based on the developed concept, a particular method for analyzing the dynamic vulnerability has been developed, which addressed sub-Q.1 and sub-Q2.

Notably, the conventional diversity evaluation approach focuses only on the supply amount of electricity based on the concept of sufficiency and this study also monitors only the power balance between demand and supply after the sudden drops of generation capacity caused by sudden disturbances on power facilities. As such, the comparison of static and dynamic vulnerability could be conducted under the same platform and this assumption of this study would be justified in the case of diversity narratives.

To apply the developed approach for evaluating dynamic vulnerability, this study conducts the case studies as follow.

The core of dynamic vulnerability in this study is based upon the self-sufficiency of power system without any reliance on externalities even after sudden disturbances on facilities of power source. Due to this essential, this study assesses the standalone power system disconnected with any other external power network, which would correspond to the worst scenario of dynamic vulnerability. This study focuses on the two types of standalone power system; that is, centralized network and distribution network. The centralized network has been a major form of power system for a long term. Power utility companies has conventionally controlled the centralized network by using a large-scale central generating facilities of fossil fuels (oil, coal and natural gas), nuclear and hydro. In attempt to reduce the excess use of fossil fuels and increase in the share of renewable energy, however, the generation paradigm is being transited from the current centralized power generation to the use of distributed power generation. Distributed generation is defined from the perspectives of location and capacity [118]. It is directly connected on customer side of on-site meter or to utility grid at the distribution-level voltages [119, 120, 121]. Its capacity mostly ranges from less than a kW to tens of MW [122, 123].

Since the vulnerability potentially contained in the system is analyzed from the perspective of balance between demand and supply alone, this study assessed the fictitious electricity system in the case studies with not considering the practical structure such as geographic location of each power generation facilities. In the static and dynamic vulnerability study, supply source type and demand are required as an input data, referring to a certain electricity system in Japan. While output capacity of each power source to some extent refers to a certain electricity system in Japan, it is changed to examine the trend of dynamic vulnerability under the condition where sufficiency of power generation to meet demand in a static state is secured. The time range of the vulnerability study focuses on a one-day snapshot. Notably, the output of power from the storage technology relies on the surplus energy generated from the other power sources, assuming that that power is only accompanied with the operation of storage technology, this study considers the storage technology as a power source in the diversity in power mix.

In particular, sudden disturbances on nuclear power in the centralized network (Chapter 4) and renewables and storage technology in the distributed network (Chapter 5) will be focused as case studies of application of developed methodology.

CHAPTER 4 : Case study in the centralized network

4.1 Introduction

In last decades, the global energy security has been critically threatened by heavy reliance on fossil fuels. The improvement of energy security is of paramount importance to achieve the sustainable development. Especially, given that the undisturbed electricity supply is essential for sustaining quality of human life, the design of strengthened electricity grid is vital to ensure continuous electricity supply.

Numerous research works on power system reliability from the viewpoint of cascading outages under external disturbances such as short circuits are hitherto published [124, 125, 126]. These existing reports principally tend to address technical and engineering failures of power grid system. Following the technical analysis, the electric utility industry has developed several performance measures to evaluate power system reliability [127, 128]. These reliability indices include measures of outage duration (System Average Interruption Duration Index (SAIDI), and Customer Average Interruption Duration Index (CAIDI)) and frequency of outages (System Average Interruption Frequency Index (SAIFI) and Customer Average Interruption Frequency Index (CAIFI)) based on the past experience data. These existing indices are practically utilized as complex metrics for evaluating reliability in the energy security narratives [25]. In addition, probabilistic method has been also utilized for the evaluation of power system reliability [129, 130, 131]. Both loss-of-load probability (e.g. [132]) and loss-of-power-supply probability (e.g. [133, 134]) are probabilistic models for examining the design of power system.

Notwithstanding the fact that technical and engineering failures of power grid system have been analyzed to evaluate power system reliability hitherto, the risk of electricity supply disruption caused by societal issues cannot be simply ignored [1]. Particularly, current societal issues of electricity supply are strongly associated with nuclear energy utilization [135]. The significance of nuclear energy supply disruption can be well observed through the energy situation of Japan after the Fukushima Daiichi nuclear power plant accident. In the aftermath of the Fukushima nuclear accident, all nuclear power plants in Japan, which had previously contributed approximately 30 % of the electricity supply, were shut down due to the request for reevaluation of safety performances, which led to the nationwide electricity shortage [109]. In order to cope with unavoidable energy shortage, Japanese government conducted planned power cuts [136], which led to the immediate electricity supply disruption. This critical situation of electricity supply revealed that the sudden supply disruption particularly associated with nuclear energy utilization should be considered as a new and significant risk to domestic energy supply security. In addition, other several reasonable societal issues such as lawsuit arising from public opposition movement [111], and notice of nuclear terrorism [112] would have potential to cause sudden disruption of nuclear energy supply.

Given that nuclear power share is expected to expand worldwide even after the Fukushima nuclear accident due to the acceleration of energy demand [137, 138] and the core of energy security concerns is the risk of national vital energy services [139], it would be crucial to consider possible consequences of the potential disruption of nuclear energy supply for evaluating the security performance of electricity supply system. However, quantitative analysis of a set of relation between the sudden nuclear energy supply disruption and its impact on continuous electricity supply security (hereafter referred to "nuclear vulnerability") has only been scarcely discussed.

This Chapter will quantitatively assess nuclear vulnerability based on the concept of system security. Hu et al. examined recovery process from localized disturbances for evaluating the reliability of power system [140]. Hazi et al. analyzes the maximum restoration time after interruptions as the electricity reliability indicator [141]. This study focuses on the controllability of alternative energy sources such as thermal power and pumped-storage hydro. This characteristic can support the continuous electricity supply even after the sudden stoppage of nuclear operation occurs. As such, nuclear vulnerability is analyzed based on the condition of both different magnitude of sudden stoppage of nuclear operation and the different time instant of stoppage occurrence, where the whole grid ends up not being able to meet the demand despite of the full of thermal power operation. Nuclear vulnerability analysis can provide the prediction of continuous electricity supply, which will help the utility manager to make an appropriate action based on the information on both the magnitude and the time instant of sudden stoppage of nuclear operation.

It must be mentioned that the aforementioned existing reliability indices are computed based on the past experience of the whole grid system and have been seldom used to predict the risk of electricity supply disruption corresponding to the different capacity combination of various energy sources. These indices also do no cover the concept of sudden supply disruption. However, the grid operation will require the more sophisticated index particularly associated with nuclear power utilization in which the future prediction on the risk of electricity supply disruption is presented to ensure the continuous electricity supply security [124]. Hence, through nuclear vulnerability analysis a new predicted electricity supply security index dedicated for nuclear power utilization will be provided in this research. No academic works on an application of amount of time the system can remain self-sufficient after the occurrence of sudden disturbances into the reliability index has been hitherto published.

Besides power system reliability associated with nuclear energy utilization, both diversification of electricity mix and redundancy of capacity sizing of electricity generation have been widely reported as major attributes to evaluate the security of continuous electricity supply and to improve the design of strengthened power system [10, 25, 142]. Especially, nations heavily relying on fossil fuel imports suffer from severe vulnerabilities of geopolitical stability [143]. Diversification of electricity generation by energy source type is essential to improve energy supply security [20]. Meanwhile, the concept of redundancy represents the reserve margin which is incorporated into energy system for external disturbances [144]. Adequate power system with spare capacity achieves the uninterrupted physical infrastructure [145]. Based on these considerations, both of diversification and redundancy should be incorporated with nuclear vulnerability to design the power system taking into account the risk of nuclear energy utilization.

As such, the objective of this Chapter is to establish the methodology of quantifying nuclear vulnerability in order to develop a new electricity supply security index dedicated for nuclear power utilization. This Chapter also aims to analyze the relationship of three major attributes for evaluating stable electricity supply system; diversification, redundancy and nuclear vulnerability. This Chapter addresses sudden disturbances with a focus on nuclear power in the centralized network as a case study of application of developed methodology for dynamic vulnerability in energy security.

This Chapter proceeds as follows. Firstly, the methodology of developing the continuous electricity supply security index dedicated for nuclear power utilization is presented in Chapter 4.2. Subsequently, Chapter 4.3 analyzes the nuclear vulnerability quantitatively. In addition, the relationship between diversification, redundancy and nuclear vulnerability is evaluated in Chapter 4.4. Finally, Chapter 4.5 concludes this study.

4.2 Methodology

The methodology in this section consisting of construction of electricity supply model, development of the new electricity supply security index dedicated for nuclear power utilization and analysis of the three attributes comprising of diversification, redundancy and nuclear vulnerability is presented in this section.

4.2.1 Construction of electricity demand and supply model

A reference case in this study for analyzing the impact of nuclear vulnerability on continuous electricity supply security is a certain centralized electricity system in Japan. This system included a significant share of nuclear energy in the region's electricity supply mix. Fukushima nuclear accident indirectly had an unavoidable impact on the electricity supply security in this system despite of no physical damage to the electricity grid components; nuclear power had a considerable share of approximately 25% of capacity and 44% of generated electricity in 2010 [146], but all of its capacity has been turned off after the Fukushima nuclear accident. Even though this centralized system has a large sized PV and solar power plants, the share of renewable power is a mere 1.5 % at present and thus the renewable power contributing to centralized grid is not considered in this model. Furthermore, electricity generated by distributed generations or transferred from the other area is not included for simplicity.

The fictitious centralized electricity demand and supply model is constructed by using System Dynamics, given in Figure 4.1. System Dynamics can be used for the modeling power supply flow [147]. The electricity demand and supply model consists of the various power supply; oil, liquefied natural gas (LNG), coal, nuclear, hydro and pumped-storage hydro. Coal, nuclear and hydro act as the base load, while the middle and peak load is represented by oil, LNG and pumped-storage hydro. The summation of all electricity generated by each of energy sources is referred to as grid electric power. The grid electric power is delivered to the grid demand. Meanwhile, any grid surplus power which is not consumed by the grid demand will be channeled to the pumped storage hydro. The pumped-storage hydro is considered as the large-scale storage system and modeled here as such. The power will be generated by pumped-storage hydro when the combined power from oil, LNG, coal, nuclear and hydro does not meet the grid demand. The time scale of model simulation is one-day.

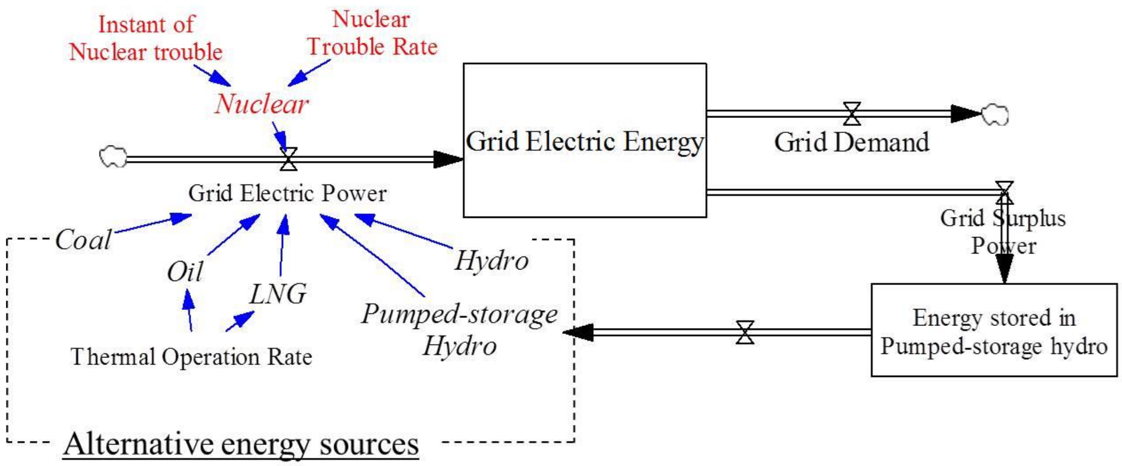

Figure 4.1 Electricity demand and supply model

It must be noted that in this analysis the nuclear power operation is further influenced by both the magnitude and time instant of sudden stoppage of nuclear power plants. The magnitude of sudden stoppage of nuclear power plants and time instant of sudden stoppage of nuclear power plants are respectively indicated as nuclear failure rate and instant of nuclear failure.

The main components of electricity demand and supply model are "grid demand", "grid electric power", "grid surplus power", and "energy stored in pumped-storage hydro" as summarized in Table 4.1.

Table 4.1 Main components of electricity demand and supply model

Element	Role
Grid demand	Reference daily load curve corresponding with representative peak load curve
Grid electric power	Summation of all electricity generated by each power plants at any given time
Grid surplus power	The difference between “Grid Demand” and “Grid Electric Power”
Energy stored in pumped-storage hydro	The energy which can be used by pumped storage hydro

It must be mentioned that the simulation results are expected to be changed depending on the load profile. The present study uses a reference daily load curve for maximum demand day published by the government [148] as input for grid demand. The input of maximum demand load profile is considered as the most severe case of electricity supply security. In addition, it is assumed that the load profile does not change from the reference case even after sudden stoppage of nuclear power operation occurs. The location and magnitude of occurrence of natural disaster cannot be predicted in a precise manner, which leads to critical difficulties of demand projection after the occurrence of natural disaster. However, observations of demand profile after Fukushima accident indicate that the electricity consumption is highly expected to be reduced after the occurrence of natural disaster. As we have utilized the most severe load profile in the analysis and did not change the load profile even after the natural disaster, the results could be interpreted as the worst case in terms of supply interruption. Given that the most severe case represents the worst nuclear vulnerability, the practical outcome in the real situation is highly expected to be more secured than this analysis.

Several notable characteristics of this model are as follows:

1. The operation of thermal (oil, and LNG) and pumped storage hydro could be controllable. The

thermal (oil and LNG) operation rate is referred to Thermal Operation Rate.

2. The minimum and maximum thermal operation rate is 10% and 100% respectively.
3. The pumped storage hydro will start its operation after the thermal operation rate reaches the maximum thermal operation rate.
4. Pumped storage hydro is assumed as follows:
   - The amount of water for the pumped up is not considered for simplicity.
   - The surplus power is calculated including the previous day's demand. This previous demand is inputted as the same value of this day.
   - Pumped storage hydro power plant does not work as inflow type hydro power plant.
5. Input power capacities in the fictitious centralized system are as summarized in Table 4.2.

Table 4.2 Input power capacity in the fictitious centralized electricity system

Electricity component	Capacity (MW)
Nuclear	9760
Oil	6220
Coal	1800
LNG	8010
Hydro	3320
Pumped storage hydro	4880

4.2.2 Development of the dynamic vulnerability index dedicated for sudden disturbances on nuclear use

As mentioned in Chapter 4.1, nuclear vulnerability is the risk of electricity supply disruption caused by the sudden stoppage of nuclear power operation. Quantitative nuclear vulnerability analysis is conducted in this section to provide the new predicted electricity supply security index dedicated for nuclear power utilization, named System Interruption Nuclear Vulnerability Index (SINVI).

4.2.2.1 Nuclear vulnerability

The electricity demand and supply balance has to be matched to ensure the continuous electricity supply security.

Firstly, the minimum nuclear capacity in this system will be identified. Here, this paper newly define nuclear capacity rate as simulated nuclear capacity over the present installed nuclear capacity with and the present nuclear capacity rate is defined as 1.0. The nuclear capacity rate is decreased by step of 0.1 to clarify the energy deficit in the electricity demand and supply balance. Subsequently, the energy deficit will be analyzed to identify the minimum nuclear capacity rate. Under this analysis, the capacity of all other electricity sources remains the same.

Finally, nuclear vulnerability is analyzed based on the observation of thermal power (oil and LNG) operation rate under the different nuclear failure rate as well as the different instant of nuclear failure. The increase of thermal operation rate in response to the nuclear failure will generate the more surplus power, which leads to the increase of power output from pumped-storage hydro and compensates the loss of nuclear power. Several conditions are assumed as follows:

- All of the power plants except nuclear remains uninterrupted.
- In-built capacity of electricity generation in a referred certain electricity system in Japan is used as input.
- Time lag of increasing thermal operation rate in response to sudden nuclear supply disruption is not considered.

The nuclear vulnerability will be here expressed by using *RI curve*, as one of the application examples of dynamic vulnerability in fuels, presented in Chapter 3.2. The detailed steps adapted for this Chapter is presented as follows:

1. The parameters in the electricity demand and supply model is initialized. The nuclear failure rate is set as zero, which means no nuclear power plants in this area turn off. The time instant of nuclear failure is set as 00:00. The thermal operation rate is 0.1 of the minimum thermal operation rate.
2. The model simulation runs to ascertain whether the energy deficit can be observed in the electricity demand and supply balance. The energy deficit will be caused when the demand is greater than the combined power of all energy sources.
3. Unless the electricity demand and supply balance contains the energy deficit, the model simulation will be repeated with the nuclear failure rate increased by step of 0.01 until the energy deficit occurs. Once the energy deficit occurs, the previous nuclear failure rate is recorded as an available nuclear failure rate.
4. Steps 2 and 3 are repeated with time instant of nuclear failure increasing by 00:01 until 24:00.
5. The recorded available nuclear failure rate corresponding to all samples of instant of nuclear failure is plotted on the nuclear failure rate versus the instant of nuclear failure.

4.2.2.2 Computation of nuclear vulnerability to obtain the SINVI dedicated for nuclear power utilization

The new predicted electricity supply security index dedicated for nuclear power utilization will be obtained after plotting the available nuclear failure rate as the *RI curve* in the previous section. The SINVI is defined as the faction of the region above the curve connected with each available nuclear failure rate in the graph to the sum of all regions.

4.2.3 Analysis of the relationship between diversification, redundancy and nuclear vulnerability

In order to design the strengthened electricity grid from energy security perspective, several attributes are used to evaluate the continuous electricity supply security. This paper analyzes the relationship of three attributes comprising of diversification, redundancy as well as nuclear vulnerability to improve the electricity supply security.

Firstly, given that both the in-built capacity share and the total installed capacity affect nuclear vulnerability, the developed nuclear vulnerability analysis will be conducted based on the different input capacity data. Both nuclear and thermal (oil, and LNG) are selected to change input capacity data for simplicity. Particularly, the minimum required total installed capacity has to be identified.

Subsequently, the quantitative calculations of diversification, redundancy and nuclear vulnerability will be executed.

Herfindahl-Hirschman Index (HHI) will be used to quantify diversification. HHI has been commonly accepted to measure concentration of the given samples [149, 150]. It must be noted that there are two approaches to evaluate diversification; the energy base (how much energy each of all electricity sources totally generates throughout one day) and the capacity base (how much capacity each of all electricity sources installs). In this analysis, both two approaches will be used to evaluate diversification. HHI in the energy base is calculated by squaring the ratio of energy generated by each of all electricity sources to the total energy generation and summing the resulting number. In contrast, HHI in the capacity base is calculated by squaring the ratio of installation capacity of each of all electricity sources to the total installation capacity and summing the resulting number. Lower value of HHI corresponds to higher diversity. Hydro is here considered as the different power source from pumped storage hydro in HHI calculation. The model simulation runs under the various combinations between nuclear and thermal (oil, and LNG).

The total installed capacity between nuclear and thermal (oil and LNG) is used to quantify redundancy. The total installed capacity between nuclear and thermal (oil and LNG) is calculated by multiplying the present sum of installed capacity between nuclear and thermal (oil and LNG), which is 23990MW, with the total installed capacity rate.

The developed new index – SINVI - is used to quantify nuclear vulnerability.

Finally, the computed values of diversification, redundancy and nuclear vulnerability is plotted on the SINVI versus HHI to analyze the relationship between the three main attributes for the better design of power system capacity.

4.3 Results and discussion for SINVI analysis

4.3.1 Identification of the minimum required nuclear capacity rate

In order to analyze the nuclear vulnerability, the minimum required nuclear capacity rate is firstly identified. Given that the grid has to ensure the continuous electricity supply security, electricity demand and supply balance is presented with nuclear capacity rate decreased by step of 0.1. Especially, the difference of balances under the nuclear capacity rate between 0.4 and 0.3 has to be noted, given in Figure 4.2. Due to the insufficient capacity, the surplus power corresponding to the shaded region above the demand has to be generated and stored in the morning when demand is relatively lower. This stored surplus energy is utilized in the peak time by the operation of pumped-storage hydro. When the nuclear power rate of 0.4, the demand and supply balance is matched. In contrast, when the nuclear power rate is 0.3, there is a certain region (uncolored region in Figure 4.2) where the generated power cannot meet the grid demand and thus leading to the electricity supply shortage; the total area of this region will be referred as “energy deficit”. Taking into consideration that the supply shortage occurs for nuclear capacity rate between 0.4 and 0.3, the energy deficit in this range of nuclear capacity rate is calculated and is shown in Figure 4.3. It can be observed that nuclear capacity rate of 0.38 is obtained as the minimum required nuclear capacity rate in our model. Under the nuclear capacity rate of 0.38, 100% operation of thermal (oil and LNG) throughout one day is required to match the supply with demand.

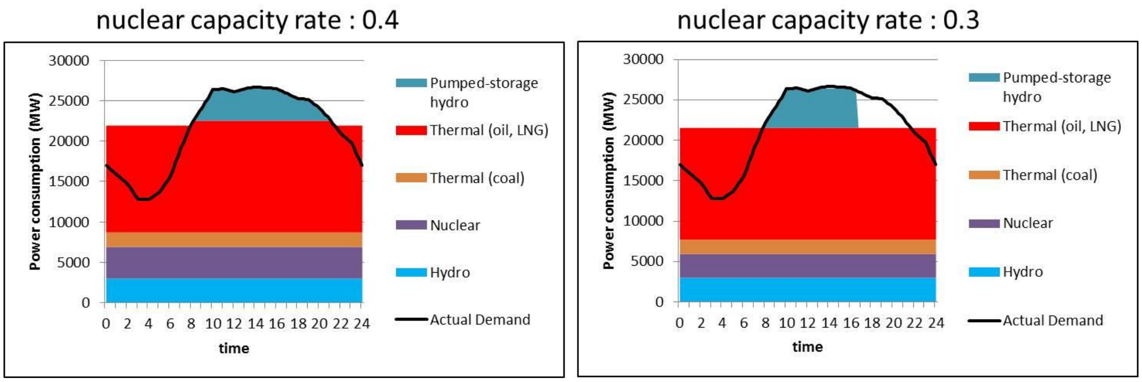

Figure 4.2 Electricity demand and supply balance under the nuclear power capacity of 0.4 and 0.3

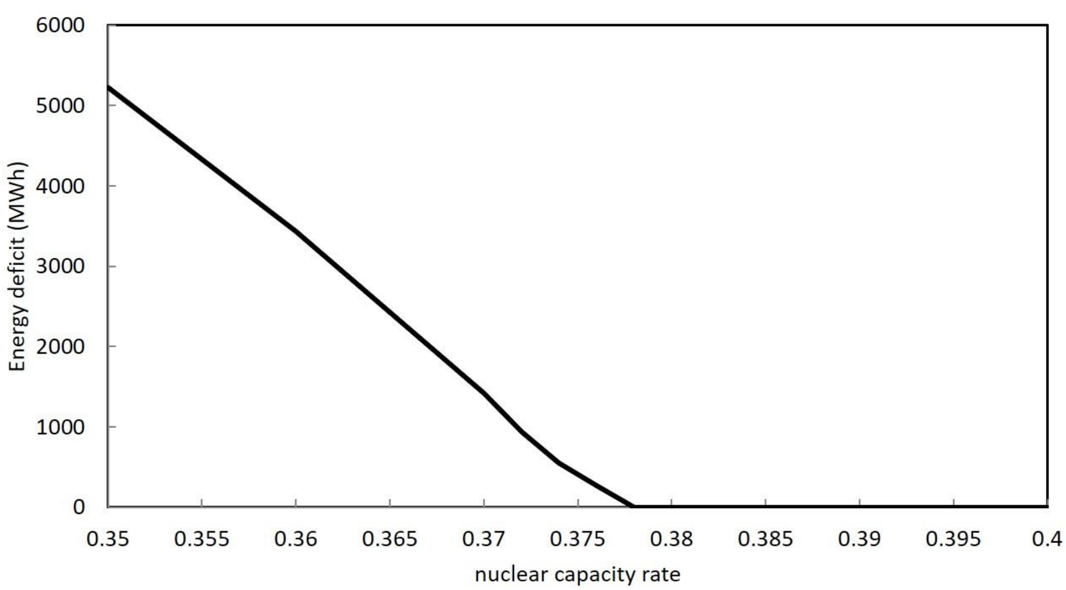

Figure 4.3 Energy deficit under the different nuclear capacity rate

4.3.2 Nuclear vulnerability analysis

The nuclear vulnerability analysis is subsequently conducted following the established steps. The available nuclear failure rate is denoted on the graph of nuclear failure rate versus instant of nuclear failure. The result of available nuclear failure rate, also known as nuclear vulnerability curve, is given in Figure 4.4. Nuclear vulnerability curve declines with time from the nuclear failure rate of 0.6 at 0:00 to the nuclear failure rate of 0.3 at 9:30. The curve then gradually increases with time up to the nuclear failure rate of 1.0 at 20:23. The electricity supply in this system can meet the demand on this day under nuclear vulnerability curve, while the electricity supply disruption is caused unless importing power generated outside or cutting the demand above the nuclear vulnerability curve. In addition, the intersecting points between nuclear vulnerability curve and nuclear failure rate are particularly considered as the vital instant time of nuclear failure, named the time boundary. This time boundary determines the ability of the grid to maintain the electricity supply security even after a certain magnitude of nuclear power disruption occurs. As such, the electricity system can be strengthened with nuclear vulnerability curve denoted upward and the time boundary narrowed.

It must be noted that the identified minimum required nuclear capacity rate is 0.38. This corresponds to the nuclear failure rate of 0.62, which is shown as the horizontal scatter line in Figure 4.4. The intersecting point of nuclear vulnerability curve and the minimum nuclear capacity rate line is at 17:23. In summary, Figure 4.4 can be divided into 4 regions:

- Region A - Even if nuclear sudden supply disruption happens under this condition, the system can manage to supply electricity without importing any electricity on this day and the following day.
- Region B - If nuclear sudden supply disruption happens under this condition, the system has to import electricity or cut demand on this day, but since the following day it can manage by itself without the need of imported electricity.
- Region C - If nuclear sudden supply disruption happens under this condition, the system has to import electricity or cut demand on this day and the following day.

- Region D - If nuclear sudden supply disruption happens under this condition, the system can manage to supply electricity only inside area but it has to import electricity or cut demand on the following day.

This nuclear vulnerability analysis can provide the prediction of continuous electricity supply security, which will help the utility manager to make an appropriate action after the sudden stoppage of nuclear power operation based on this developed nuclear vulnerability curve.

It must be noted that the flexibility of controlling thermal operation rate in respond to the sudden stoppage of nuclear power operation is of critically importance to mitigate the risk of electricity supply disruption. The advanced information exchange is required through the improvement of Information Technology such as Smart Grid, which allows for computer-based remote control and automation through two-way communication. In addition, the increase of storage technology capacity is also vital to strengthen security of continuous electricity supply particularly in the short-term. The more installation of plug-in vehicle in the building sector will help to mitigate the short-term impact of sudden stoppage of nuclear power operation.

To quantify the potential vulnerability of electricity supply disruption particularly associated with nuclear power utilization, the SINVI is defined as the fraction of the sum of regions B and C of Figure 4.4 to the sum of total regions. The lower SINVI corresponds to the less nuclear vulnerability. Since the nuclear vulnerability is strongly related to the sudden nuclear energy supply disruption, region D is not included in the definition of calculation. The SINVI for the present case is 0.43.

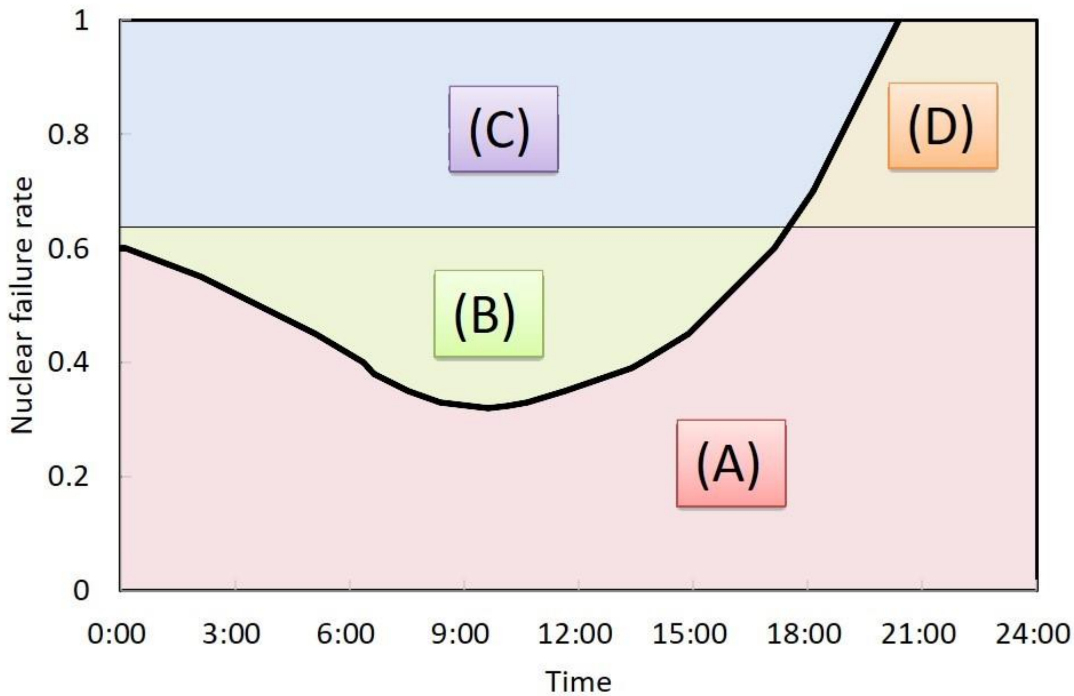

Figure 4.4 Interrelation between time boundary and nuclear failure rate

4.4 Results and discussion for the analysis of the relationship between diversification, redundancy and nuclear vulnerability

The SINVI depends on the inputting data of both grid electricity configuration and the total grid capacity, associated with diversification and redundancy respectively. This section focuses on the analysis of the relationship between diversification, redundancy and nuclear vulnerability.

4.4.1 Identification of the minimum required total installed capacity rate

In order to identify the minimum required total installed capacity rate, this model runs with both nuclear capacity rate and thermal (oil and LNG) capacity rate decreased at the same rate. This corresponds to the total installed capacity rate. The present total installed capacity rate is normalized to unity, and the capacity ratio of nuclear to thermal (oil, and LNG) remains the same as the present. This model simulation checks whether the energy deficit is observed in the electricity demand and supply balance. The result is shown in Figure 4.5. Under more than 0.75 of the total installed capacity rate, the electricity supply in this system can meet the demand. In contrast, under less than 0.74 of the total installed capacity rate, there is energy deficit, causing the electricity supply disruption. In summary, the minimum required total installed capacity rate is 0.75.

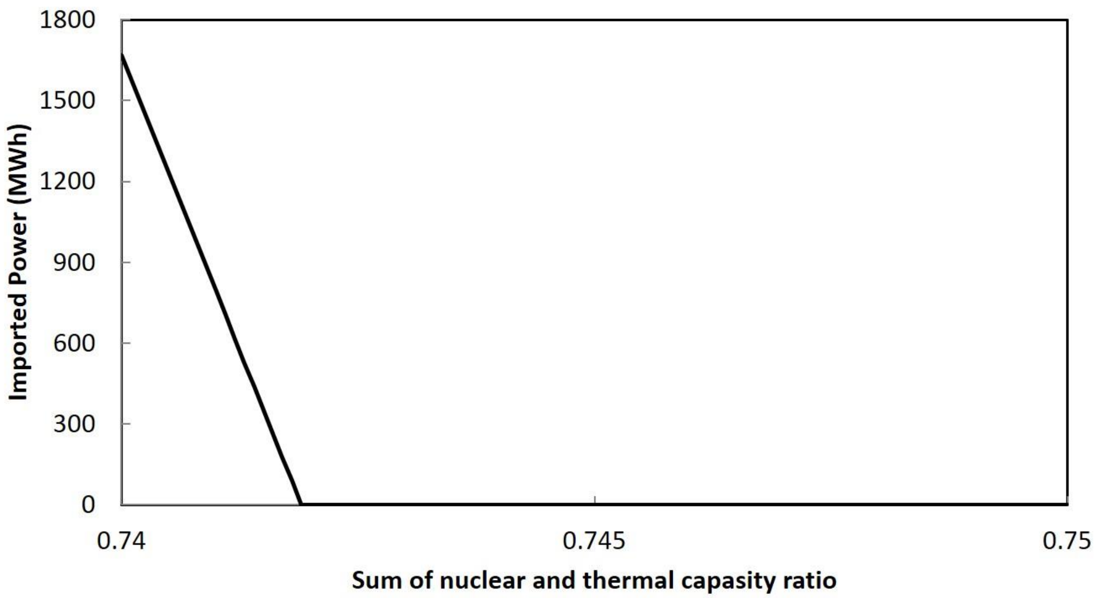

Figure 4.5 Identification of the minimum required total installed capacity of both thermal (oil and LNG) and nuclear

4.4.2 Parametric analysis of nuclear vulnerability

Parametric analysis of nuclear vulnerability was conducted under various conditions for both nuclear and thermal (oil and LNG) capacity.

Firstly, the nuclear vulnerability was analyzed changing the capacity ratio of thermal (oil and LNG) to nuclear under the present total installed capacity rate. The scenario is composed of nine possible combinations of thermal (oil and LNG) : nuclear ratio: 9:1, 8:2, 7:3, 6:4 5:5, 4:6, 3:7, 2:8, and 1:9. The result is shown in Figure 4.6.

The least impact of nuclear vulnerability is achieved under the capacity ratio of 9:1. This is the scenario of least nuclear capacity share. Meanwhile, nuclear vulnerability curve is denoted downward and the width of time boundary is widened with increasing the nuclear share. In addition, less than 30% of nuclear failure even under the maximum nuclear capacity ratio (1:9) does not threaten the electricity supply security in this system regardless the instant of sudden stoppage of nuclear power operation.

It must be mentioned that the nuclear vulnerability is jeopardized more significantly in the morning with the capacity ratio of nuclear to thermal (oil and LNG) decreased. Given that the operation of pumped-storage hydro in peak time relies on the amount of surplus energy, thermal power operation control in the morning in response to the emergency is vital to generate the sufficient surplus power. As such, the adequate capacity ratio of thermal (oil and LNG) is required especially in the morning for emergency.

Subsequently, nuclear vulnerability was examined changing the total installed capacity under the present capacity ratio of thermal (oil and LNG) to nuclear. Based on the identified minimum required total installed capacity rate, 0.8, 0.9 and 1 of the total installed capacity rate was selected as the three scenarios of this analysis. Under each of three scenarios, the nuclear vulnerability curve is obtained. The result is shown in Figure 4.7.

The least impact of nuclear vulnerability is achieved under the total installed capacity rate of 1. The nuclear vulnerability is exacerbated with the total installed capacity decreased, which means securing the sufficient redundancy is of vitally importance to mitigate the nuclear vulnerability. Especially under the total installed capacity rate of 0.8, there is time duration from 9:00 to 19:36

when any magnitude of nuclear failure causes the electricity supply disruption in this system. Given that surplus power is principally generated before the peak time, energy system is more vulnerable before the peak time rather than after the peak time to sustain for one day.

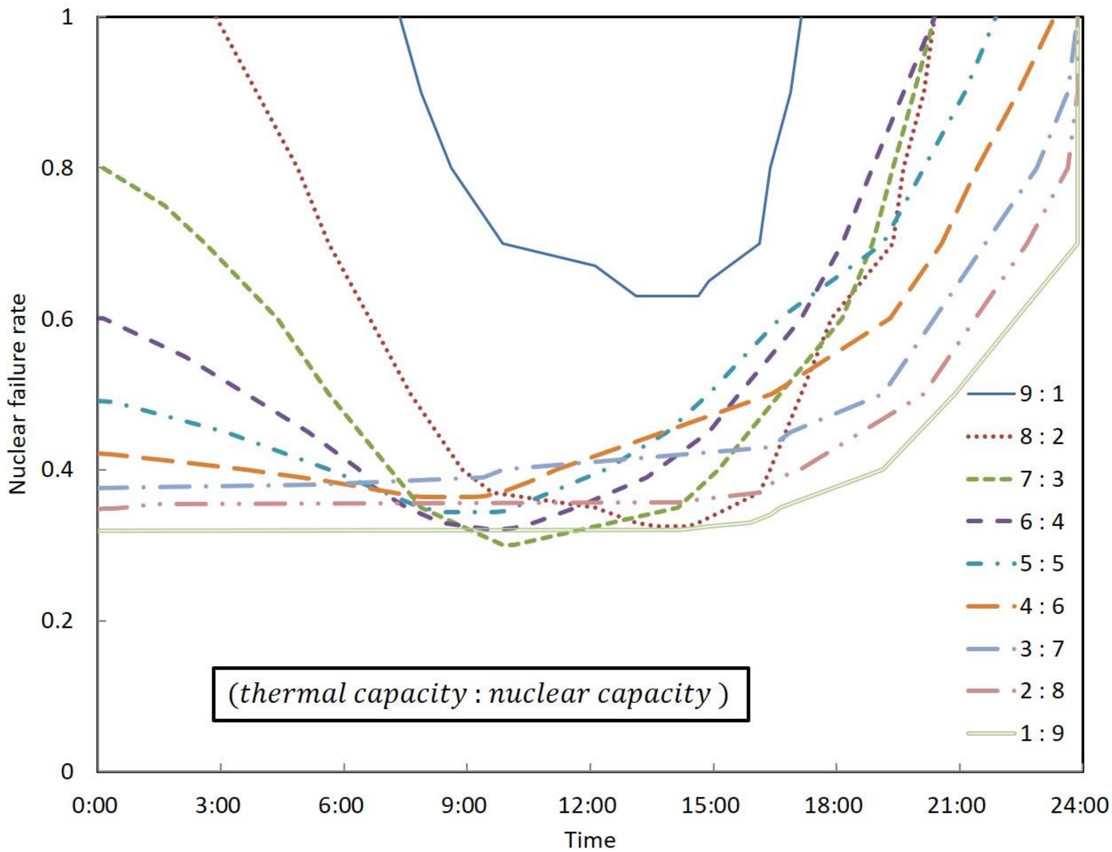

Figure 4.6 Nuclear vulnerability curve changing the capacity ratio of thermal (oil and LNG) to nuclear under the present total installed capacity rate

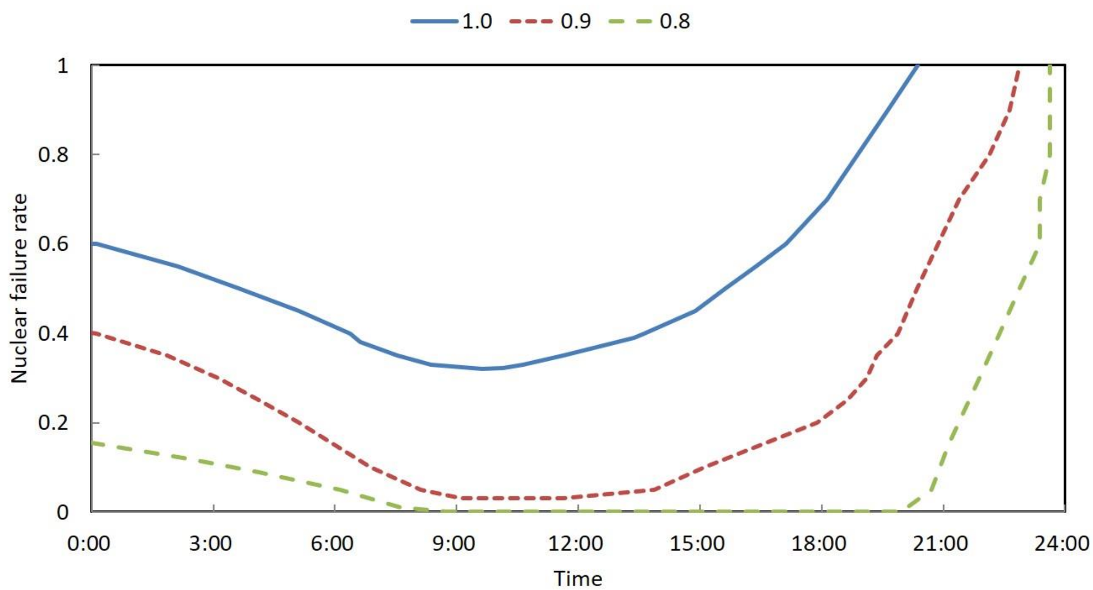

Figure 4.7 Vulnerability curve changing the total installed capacity under the present capacity ratio of thermal (oil and LNG) to nuclear

4.4.3 Relationship between diversification, redundancy and nuclear vulnerability

The computed values of diversification, redundancy and nuclear vulnerability were plotted on the SINVI versus HHI to analyze the relationship between the three main attributes for the evaluation of continuous electricity security.

Firstly, the result is given Figure 4.8 using HHI in the energy base. The vertical and horizontal axis corresponds to SINVI and HHI respectively. The curves are depicted by connecting each dot under the same total installed capacity rate of 0.8, 0.9, and 1.0, and will be called diversification-redundancy-nuclear vulnerability curve. Pertaining to HHI in the energy base, the capacity ratio of thermal (oil and LNG) to nuclear of 7:3 in the case of the total installed capacity rate of both 0.8 and 0.9 and of 8:2 in the case of the total installed capacity rate of 1 provide the best diversification of electricity configuration in this system. Meanwhile, the significant difference of HHI in energy base arises from the comparison between 9:1 and 1:9. Since the thermal operation rate is changed with time, the total energy generated by thermal (oil and LNG) in the case of 9:1 is significantly smaller than the one by nuclear in the case of 1:9.

SINVI is decreased with the capacity ratio of thermal to nuclear increased under the total installed capacity rate of 1. In contrast, this trend is not applied to the less total installed capacity rate. Under the diversification-redundancy-nuclear vulnerability curve of the total installed capacity of 0.9, the SINVI is decreased with the capacity ratio of thermal to nuclear increased from 1:9 to 5:5, and then the SINVI is significantly increased up to 7:3. Subsequently, the SINVI is decreased again from 7:3 to 9:1. Under the diversification-redundancy-nuclear vulnerability curve of the total installed capacity of 0.8, the SINVI is increased with the capacity ratio of thermal to nuclear increased from 1:9 to 3:7, and then the SINVI is decreased with the capacity ratio of thermal to nuclear increased from 3:7 to 9:1. Even under the condition of decreasing nuclear capacity share, nuclear vulnerability is jeopardized in the system which does not have the sufficient thermal (oil and LNG) capacity. As such, the combination of nuclear capacity share, the thermal (oil and LNG) capacity as well as the proper pumped-storage hydro utilization contributes to the different trend of SINVI.

Subsequently, the resultant diversification-redundancy-nuclear vulnerability curve using HHI in the capacity base are given in Figure 4.9. Although HHI is calculated based on the capacity, the different HHI under the same capacity ratio of thermal to nuclear is obtained, comparing to the different total installed capacity rate. This is because the capacities of coal, hydro, and pumped storage hydro remain the same through the model simulation under the different sum of both thermal (oil and LNG) and nuclear capacity. In addition, the capacity ratio of thermal to nuclear of 5:5 is obtained as the smallest HHI under the capacity base calculation.

It can be noted that there are differences of HHI between Figure 4.8 and Figure 4.9 under the same condition of both total installed capacity rate and the capacity ratio of thermal to nuclear. Especially the HHI scale is different from the calculation approaches. HHI in energy base is obtained in the scale from 0.2 to 0.7, while HHI in capacity base is covered from 0.25 to 0.45. As such, energy policy including the target of diversification is required to take the calculation approach into consideration.

It was discovered that the combination between diversification and nuclear vulnerability depends on redundancy to some extent regardless of whether HHI is calculated in energy base or in capacity base. It is well observed through the comparison of the two cases: the total installed capacity rate of 0.9 with the capacity ratio of thermal to nuclear of 9:1, and the total installed capacity rate of 1.0 with the capacity ratio of thermal to nuclear of 8:2. Given that the latter nuclear share obtains the better diversification, and the latter nuclear capacity of 4800MW is larger than the former one of 2160MW, the latter case rather than the former case apparently relies on nuclear power utilization. However, SINVI of the former case is worse than the latter case. This means redundancy is the main contributor to determination of nuclear vulnerability.

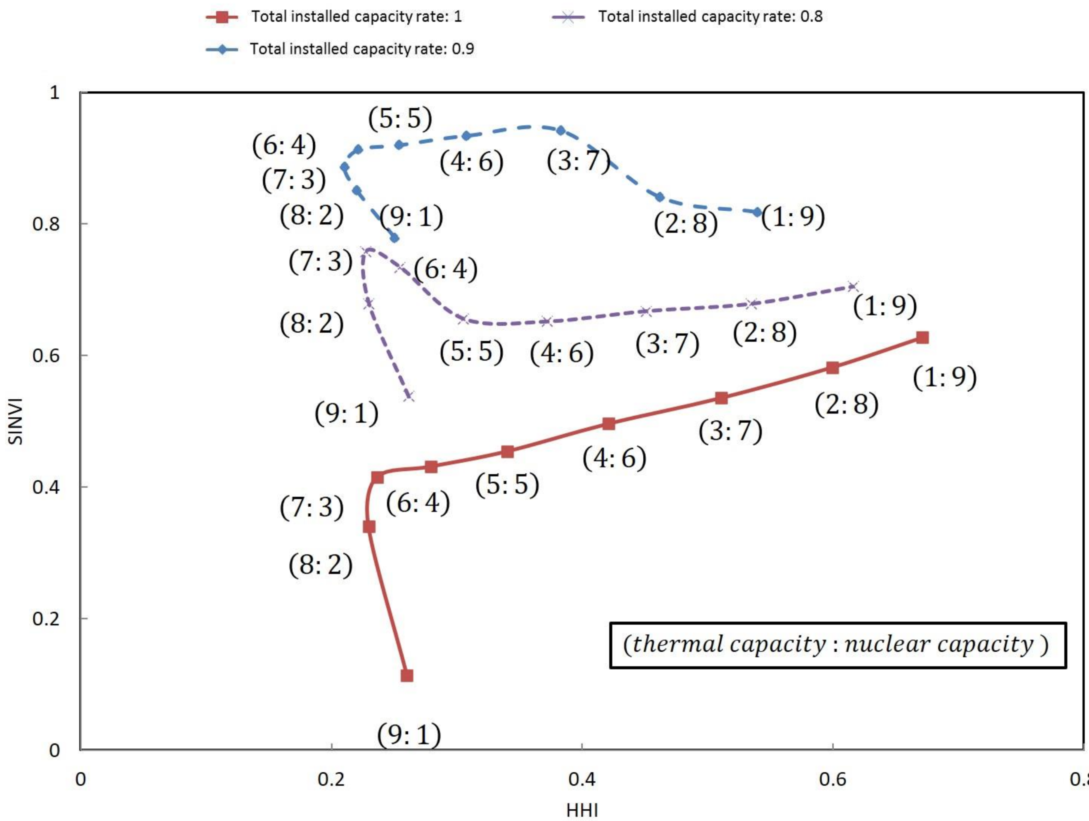

Figure 4.8 The relationship between diversification in the energy base, redundancy and nuclear vulnerability

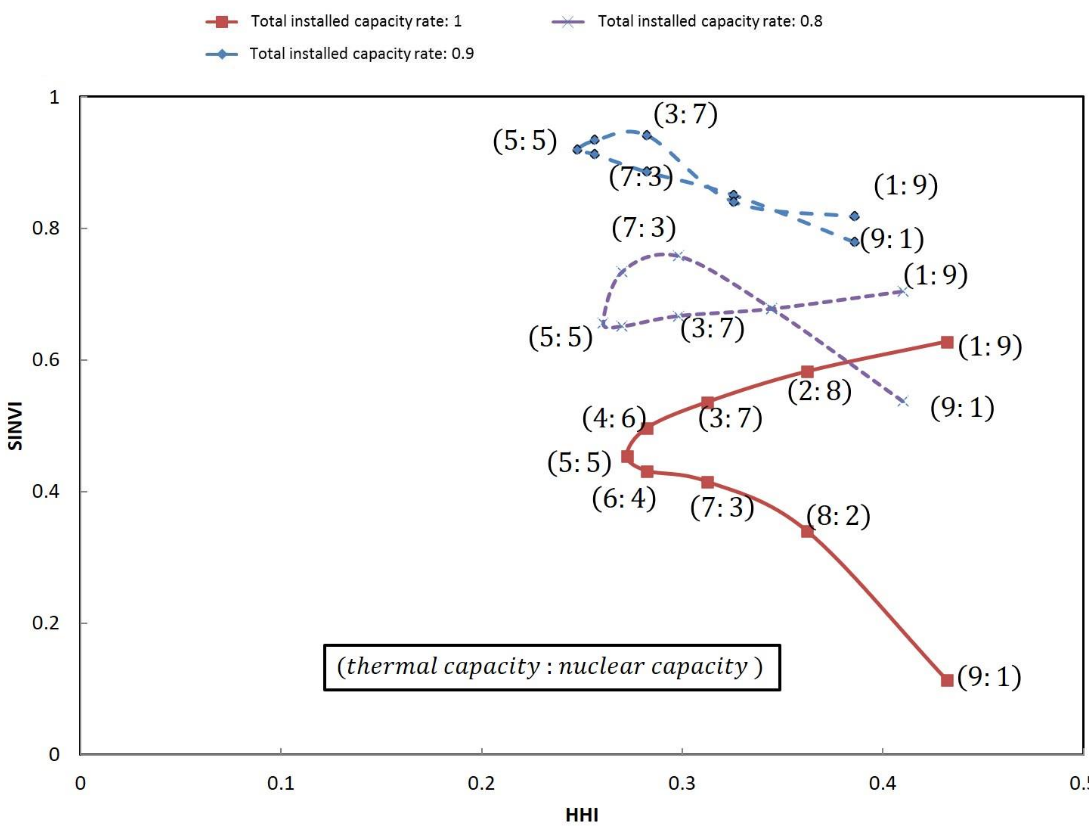

Figure 4.9 The relationship between diversification in the capacity base, redundancy and nuclear vulnerability

4.5 Conclusion

Technical and engineering failures of power grid system have been analyzed to evaluate power system reliability hitherto. Meanwhile, this Chapter has evaluated the risk of electricity supply disruption caused by the sudden stoppage of nuclear power operation arising from reasonable societal issues. The methodology of quantifying nuclear vulnerability based on the analysis under varying both the magnitude and time instant of sudden stoppage of nuclear power plants has been established. Through modelling the electricity supply flow and analyzing the nuclear vulnerability, a new electricity supply security index dedicated for nuclear power utilization, named System Interruption Nuclear Vulnerability Index (SINVI) has been developed, which has addressed sub-Q.3.

Finally, the widely proposed dimensions of energy security for undisturbed electricity supply – diversification and redundancy – have been incorporated with nuclear vulnerability to design the more secured power system by estimating the risk of sudden stoppage of nuclear power utilization, which has addressed sub-Q.4.

SINVI does not require any past data and thus could be used to predict the risk of electricity supply disruption arising from the sudden stoppage of nuclear power operation corresponding to the different capacity combination of various energy sources. Such analysis based on fictitious capacity combinations cannot be achieved using the existing indices which rely on past data.

It has been discovered that redundancy of power system has an important role on mitigation of the nuclear vulnerability. There should be understandable reluctance towards the establishment of more secured reserves to increase redundancy because of large capital and management cost. The support from the government for investment in installing the sufficient power capacity would be one of major key factors to improve continuous electricity supply security under nuclear power utilization.

In fact, the continuous electricity supply security in Japan has been threatened due to the redundancy issue. For example, after Fukushima nuclear accident, all of the nuclear power plants in Kansai area were shut down. Given that the total installed capacity rate at that time was 0.6, electricity had to be transferred from other areas to meet the domestic demand. Units 3 and 4 of Takahama nuclear power plant in Kansai area were allowed to restart on January and February, 2016. The Nuclear Regulation Authority has also confirmed that units 1 and 2 meet new safety regulations [151]. When all of units in Takahama nuclear power plant obtain the certificate for reoperation, the capacity ratio of thermal (oil, and LNG) to nuclear becomes 8:2. Since the total installed capacity rate in this case is 0.73, however, Kansai area still needs to rely on the electricity import. Even if restart of some units of other nuclear power plants such as Mihama and Ohi allows Kansai area to manage the electricity supply without reliance on import and then the share of nuclear capacity is lower than before Fukushima nuclear accident, SINVI will be still threatened due to the insufficient redundancy.

The proposed diversification-redundancy-nuclear vulnerability curve can thus be utilized for the design of energy policy by setting the threshold in order to harmonize the effective utilization of nuclear energy. This threshold should depend on each country's energy landscape and should be considered as the limitation of risk acceptance in terms of nuclear energy; for instance, countries with low risk of natural disaster and having well established international electricity grid with other countries might be able to set lower threshold of nuclear vulnerability. The energy policy targeting feasible and challenging threshold would improve the energy system security and at the same time achieve the harmonization of nuclear power utilization. Understanding the interaction of diversification, redundancy and nuclear vulnerability in quantitative manner using the methodology proposed in this study could aid policymakers to make optimized decision for the nuclear power utilization.

Electricity market structure reform in Japan is underway and would potentially also affect the electricity production structure. In addition, distributed generation system will be also increased to mitigate the risk of supply disruption by centralized electricity system. Under such mixture of distributed and centralized generation system, facility location must be more carefully considered to optimize the balance between the cost and the overall performance of the system against supply disruption. This expected system requires the more detailed cost analysis as well, which would be the next step of the current study.

In summary, the proposed methodology of quantifying the nuclear vulnerability has been applied to develop a new electricity supply security index dedicated for nuclear power utilization. The established algorithm can be implemented in any other electricity grid network relying on nuclear power technology. The prediction of continuous electricity supply security after emergency particularly associated with nuclear power utilization will help the utility manager to make an appropriate action based on the information on the nuclear vulnerability analysis. Furthermore, the relationship between diversification, redundancy and nuclear vulnerability is of use to policymakers in evaluating the current continuous electricity supply security and designing a well-grounded energy policy.

This Chapter examined sudden disturbances with a focus on nuclear power among various energy sources in the centralized network as a case study of application of developed methodology for dynamic vulnerability in energy security. Sub-Q3 and sub-Q4 have been addressed under the case of centralized network.

CHAPTER 5 : Case study in the distributed network

5.1 Introduction

In recent decades, the acceleration of energy demand and fossil fuel depletion has drastically changed the global energy landscape. The use of renewables and local electricity production is increasingly being adopted in rural and urban communities. This shift has the potential to address several energy related issues such as more effective utilization of emerging technology, economic cost reduction, preservation of traditional schemes, and most importantly security of supply.

Renewable energy is a community-based type of energy, which is highly associated with the concept of local production for local consumption. The application of renewable energy has diverse advantages and disadvantages depending on the nature of the community where it is applied.

One of the most promising applications is among the least advantaged, namely rural communities which in most cases are segregated from the areas of higher economic development, and which lack of support to connect with the centralized power infrastructure. Often, these groups realize that for electricity suppliers it is not worth investing in the extension of the existing electricity grid to a remote community having a small number of inhabitants [152]. In fact, 15 percent of the global population has no access to electricity [153], The acceleration of population increase has caused the inequitable distribution of energy-related services among the underprivileged society. Ending energy poverty is of significant importance to solve the uneven balance of quality of life throughout regionally, nationally, and globally. Conventionally, they opt for more expensive, noisy and contaminating diesel-powered generation to produce electricity [154]. However, the utilization of diesel generators entails many risks, such as economic (e.g. expensive fuel cost), environmental (e.g. CO2 emissions) and of security of supply (e.g. fossil fuel depletion). Therefore, the application of self-sufficient off-grid electricity system can be of use in the remote isolated area [155] and the electricity generation in the remote area should be shifted to the utilization of renewable energy, which is particularly matched with the concept of local electricity production for local electricity consumption.

Besides its applications in remote communities, in urban contexts there is a shift from centralized electricity supply to independent distributed micro grid and self-sustained small scale power supply systems, both utilizing renewable energy. The reasons for such shift are mainly economic and of environmental concern. As a smaller scale of power flow, zero energy building (ZEB) and house (ZEH) are also considered to be a major solution from among various renewable energy technology options [156, 157]. ZEB/ZEH consumes energy produced on-site from renewables such as solar photovoltaic (PV) and exchange the power with the distributed grid [147]. Many countries have already initiated the concept of ZEB/ZEH as their future building energy target. For instance, the United States had set a zero-energy target of 50 percent for commercial buildings by 2040 and net zero target for all commercial buildings by 2050 [158], whereas other countries have also set their own targets.

Given the stochastic and intermittent characteristics of renewables such as the solar photovoltaics (PV), the installation of storage technology in the hybrid renewable energy system is of significant importance. In spite of drawbacks of storage technology (e.g. the capital and maintenance costs and unavoidable energy losses through the round-conversion process [159, 160]), the process of storage technology charging and discharging contributes to the power and load levelling and maintains the power stability [161]. Particularly, the standalone mode of power system requires the storage technology to store the excess energy produced by renewables so that it can play a role of energy source to meet the demand when the demand surpass the power from renewables. The contribution of storage technology to the continuous electricity supply cannot be simply ignored [162].

Given the promising future of distributed network, the appropriate design of installation capacity size is of paramount concern. It has been widely mentioned that the reliable electricity supply using both renewable energy and storage technology can be achieved with the increase in the redundancy of system installation capacity [144]. In contrast, the excessive installation of system capacity requires the more capital and operation cost. As such, the analysis of interaction of power reliability with cost has been widely conducted as an approach to sizing installations [163].

The dynamic condition of the power system has been simply dimmed out from the measurement of continuous power supply in the research topic on the hybrid renewable and storage system, as previously presented. The dynamic behavior of power system arises from the sudden disturbances in facilities of renewable energy and storage technology. The cause of failure might be human error; such as damage on the terminal base due to construction failure or screw loosening; technical error, such as burning due to the heat generation from the module, dirt and damage on the panel, or accidental connection; or environmental phenomena such as lightning, fallen trees, or weeds [164].

Given that the analysis of power security in off-grid distributed system is still at infancy, the application of dynamic vulnerability in such a system has been scarcely executed for determination of capacity size. In particular, dynamic vulnerability is highly relevant to the ability of power system to withstand sudden disturbances, called system security in the power reliability narrative. The cost effectiveness analysis from the system security perspective through the detailed assessment of system operation after the occurrence of sudden disturbances is of significantly importance to ensure the more reliable distributed electricity system. Furthermore, this system security analysis would hopefully assist in providing a different approach for designing the installation of both renewable energy and battery.

As such, this Chapter proposes the methodology for quantifying the system security of off-grid distributed network against dynamic vulnerability caused by sudden disturbances on renewables and storage technology. Furthermore, following the proposed methodology the newly index evaluating both cost and power security is established and the cost-effectiveness analysis from the system security perspective is conducted for the determination of capacity size. The sudden disturbances on renewables and storage technologies in distributed network are independently analyzed in this Chapter as a case study of application of developed methodology for dynamic vulnerability in energy security.

This Chapter is structured as follows. Chapter 5.2 establishes the methodology for determining the capacity size of both the renewable energy and storage technology dedicated for the off-grid system considering sudden disturbances. Subsequently, results are presented through the analysis of the trade-off between system security and cost in Chapter 5.3, Chapter 5.4 and Chapter 5.5. Finally, Chapter 5.6 concludes this study.

5.2 Methodology

5.2.1 Scope of research

There are various potential applications of storage technology with renewable energy depending on the scale of the standalone system. As a starting point and for simplicity, this study focuses on the case of households making the standalone electricity system. Home electricity demand and supply would be the simplest analysis of renewable energy use and storage and as such is adopted by the authors. Taking an imaginary case of a standalone zero energy home (ZEH) as a starting point, the assessment of system security after the occurrence of a sudden disturbance can be applied to any real standalone electricity system. In addition, it is of interest to the authors to select Japan for the analysis of the fictitious standalone ZEH, given its potential in urban contexts [165], and the targets set by the Japanese government to promote it [166].

5.2.2 Standalone distributed system modelling

System Dynamics (SD) is utilized to model the power flow in the standalone ZEH considering sudden disturbances on solar PV and on battery shown in Figure 5.1 and Figure 5.2, respectively. The standalone distributed network contains two supply elements: renewable energy and storage technology. Solar PV and battery correspond to renewable energy and storage technology, respectively. Given the minimum maintenance and convenient portability, solar PV is suitable for standalone ZEH [167]. The summation of power produced by solar PV and battery is defined as power delivery. The power delivery is utilized to meet the demand of home electricity, and surplus power exceeding demand is automatically transferred to the battery for storage. The energy stored in the battery is discharged when the home electricity demand surpasses the power generated by solar PV. It is assumed that the solar PV stops its operation once the battery is fully charged. The maximum demand load curve in Japan [168] is utilized as the input for demand of home electricity in this study.

Power generated by solar PV is computed based on various components. Roof-top area is multiplied with the solar panel rate to obtain the solar PV panel rate. Greater solar panel rate increases the capacity of solar PV. The irradiation data is taken from the solar irradiation data in Japan, focusing on the date of maximum load demand [169]. The average house area in Japan (140 m^2) is used as input of roof-top area, and 19% of the converting efficiency of crystalline silicon solar cells as input of PV efficiency [170]. In sum, the power generated by solar PV is computed in the following equation.

$$\text{“Solar PV”} = \text{”Roof-top area”} \times \text{”PV efficiency”} \times \text{”radiation”} \times \text{”solar panel rate”} \tag{5.1}$$

Additionally, the use of Li-ion battery is assumed in the model since it is the most common battery type for the small scale of power system. Thus, 92% is taken as the battery efficiency factor [171]. All variables with corresponding definitions and units are summarized in Table 5.1. The time range of the vulnerability study focuses on a one-day snapshot, and certain capacities of solar PV and battery are used as input under the condition where sufficiency is secured during one day. Particularly, to demonstrate the dynamic vulnerability in the distributed system when both solar PV and battery, only a sunny day was selected as a case study. In other words, the feasibility of off-grid distributed system in the real world during the longer duration such as one year or lifetime is out of scope. Notably, the output of power from the battery relies on the surplus energy generated from the other power sources, assuming that that power is only accompanied with the operation of battery, this study considers the battery as a power source in the diversity in power mix.

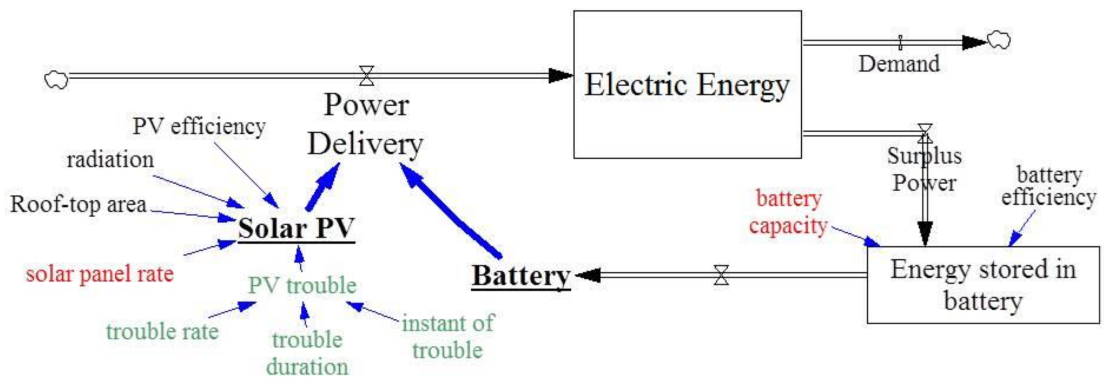

Figure 5.1 Standalone distributed system model for sudden disturbances on solar PV

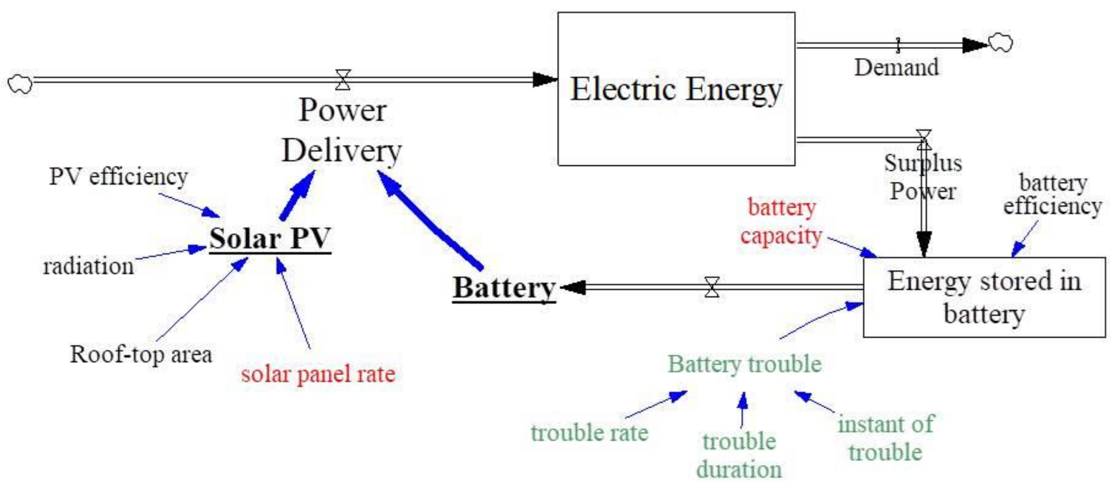

Figure 5.2 Standalone distributed system model for sudden disturbances on battery technology

Table 5.1 Definitions of variable

Variable	Unit	Definition
Solar PV	W	Power generated by roof-top solar PV
PV efficiency	%	Conversion efficiency from solar irradiation to power
Radiation	W/m^2	Solar irradiation
Roof-top area	m^2	Home roof-top area
Solar panel rate	%	Rate of solar panel area to roof-top area
Power Delivery	W	Summation of power from solar PV and battery
Electric Energy	Wh	Imaginary energy differences between the sum of demand and surplus power, and power delivery
Demand	W	Load demand of home electricity
Surplus Power	W	Excess power not consumed by load demand
Energy stored in battery	Wh	Energy stored in battery
Battery efficiency	%	Battery round-trip efficiency
Battery capacity	Wh	Maximum energy stored in battery

5.2.3 Identification of possible capacity range of both solar PV and battery

The fictitious distributed system must ensure the continuous electricity supply to meet the demand within a one-day snapshot assessed as a time range of this study. This model simulation runs from 00:00 hour. *Energy stored in battery* at the previous day has to be extracted to deliver the power before the solar PV starts operation in the morning. As such, the minimum required energy left in battery at 00:00 is first obtained corresponding to the *solar panel rate* regardless with the battery capacity. The obtained minimum required energy left in battery is used as input to immobilize the initial condition of simulation. Inputting the identified minimum required energy left in the battery, then the minimum *battery capacity* under non-stoppage of PV operation is calculated corresponding to the *solar panel rate*. This minimum *battery capacity* under non-stoppage of PV operation can store the all of the surplus power. In addition, energy deficit in one-day is also computed changing the *solar panel rate* under the condition of sufficient *battery capacity* installation to identify the minimum required *solar panel rate*. In this paper, energy deficit is defined as the total lack of energy delivery in one day. Subsequently, the minimum *battery capacity* for non-disruption of electricity supply is also obtained using the calculation of energy deficit. Based on the identified minimum required *battery capacity*, the possible maximum *solar panel rate* and maximum *battery capacity* are obtained assuming the electricity capacity margin of 20%. Given that the *solar panel rate* represents the solar PV capacity, finally, the possible range of capacity combination between both the solar PV and battery is identified.

5.2.4 Analysis of sudden disturbances on solar PV

5.2.4.1 Cost

Given that levelized cost is one of the most common approaches for calculating the cost both renewable energy and battery in the off-grid electricity system [172], the cost comparison between solar PV and battery will be conducted by using levelized cost. Levelized cost of energy (LCOE) is composed of all of the system cost throughout lifetime for electricity generation technologies. It includes construction, financing, fuel, maintenance, taxes, insurance and incentive. The one-day cost of solar PV is calculated based on the LCOE. The LCOE of residential solar PV is reported as 184 – 300 $/MWh [173]. Levelized cost of stored energy (LCOS) is also composed of the lifecycle cost information of storage technologies including upfront cost, O&M costs, charging cost, usable energy over the lifetime, residual value, and financing costs [174]. The LCOS of PV integration lithium ion battery is reported as 355 - 686 $/MWh [175]. In this analysis, for simplicity the mean value of both the LCOE of residential solar PV and the LCOS of PV integration lithium ion battery is used as input (242$/MWh and 520$/MWh respectively). The cost is calculated using LCOE and LCOS throughout the one day based on the total energy produced by solar PV and battery in this analysis.

5.2.4.2 Solar PV security

The dynamic vulnerability of sudden disturbances on solar PV will be here expressed by using *DI curve*, as one of the application examples of dynamic vulnerability in fuels, presented in Chapter 3.2. In this analysis, under the extreme case of full solar PV system shutdown, the maximum *trouble duration* when off-grid electricity system still manages the continuous electricity supply is computed. The detailed steps adapted for this section is presented as follows:

1. Initialize the *PV trouble* parameter, 00:00 hour of the *instant of trouble* and 1 minute of the *trouble duration* and inputting unity of *trouble rate*.
2. Run the simulation to see whether any energy deficit is generated or not.
3. In the case of non-energy deficit, repeat the simulation again with the *trouble duration* increased in steps of 1 minutes. Stop the simulation when energy deficit is obtained at the first time. Record the previous maximum *trouble duration* as the sustainable duration.
4. Repeat step 2 and 3 with the *instant of trouble* increased in step of 00:01 hour until 24:00.
5. The obtained result through step 2 to 4 is plotted on the graph of the sustainable duration versus *instant of trouble*.

The area under the depicted curve (*DI curve*) is computed to quantify the concept of system security dedicated for the off-grid electricity system, named solar PV security.

5.2.4.3 Normalization

The larger value of solar PV security corresponds to the better choice, while the smaller value of cost corresponds to the better choice. Both cost and solar PV security obtained in the off-grid electricity system should be normalized to be expressed in the same unit scale. The technique of standardization (z-score) is used in this Chapter. Z-score method has been used for the standardization in the analysis on the social indicators, where deviation from the mean is calculated [176, 177, 178]. Both cost and power security are calculated as follows:

$$z_{c_i} = \frac{c_i - \mu_c}{\sigma_c} \tag{5.2}$$

$$z_{s_i} = \frac{s_i - \mu_s}{\sigma_s} \tag{5.3}$$

$$\varphi(z_{c_i}) = \frac{1}{\sqrt{2\pi}} e^{-\frac{{z_{c_i}}^2}{2}} \tag{5.4}$$

$$\varphi(z_{s_i}) = \frac{1}{\sqrt{2\pi}} e^{-\frac{{z_{s_i}}^2}{2}} \tag{5.5}$$

$$\omega(z_{c_i}) = 1 - \int_{-\infty}^{z_{c_i}} \varphi(z_{c_i}) dy \tag{5.6}$$

$$\omega(z_{s_i}) = \int_{-\infty}^{z_{s_i}} \varphi(z_{s_i}) dy \tag{5.7}$$

where, c_i is the computed value of cost, s_i is the computed value of solar PV security, μ_c is a mean of computed cost, μ_s is a mean of computed solar PV security, σ_c is a deviation of cost, σ_s is a standard deviation of solar PV security, i is the capacity combination deduced from the identified possible capacity range of both solar PV and battery.

$\omega(z_{c_i})$ and $\omega(z_{s_i})$ are used as the normalized value. The lower normalized indicators correspond to the better choice of capacity installation in the off-grid electricity system.

5.2.4.4 Cost-security index

In order to demonstrate the process of determining the capacity size combination of both solar PV and battery, the normalized value should be aggregated including the weighting factor. This Chapter uses the additive aggregation approach which is the most popular aggregation method [1]. The normalized values are first multiplied with the applied weights, and then are summed to obtain the index. This newly established index is dedicated for the standalone distributed system, named cost-security index. The computation of cost-security index can assist in providing with the information integrating cost with power security, which allows system designers to make wiser decisions on the appropriate installation of both renewable energy and battery. Less cost-security index corresponds to the better quality. The weighting and aggregation is computed in the following equation:

$$\text{cost} - \text{security index} = x\omega(z_{ci}) + (1 - x)\omega(z_{si}) \tag{5.8}$$

where, x is a weighting factor.

The condition of x is as follow:

$$0 \leq x \leq 1 \tag{5.9}$$

5.2.5 Analysis of sudden disturbances on battery

5.2.5.1 Cost

It is noteworthy that various economic indicators have also been utilized for determining the capacity size of hybrid renewable power system. These include levelized cost of energy [60], as used for analysis of sudden disturbances on solar PV, total annualized cost of system [83], and net present value [85]. Given that one of major concerns on installation of battery technology is installation capacity cost, the capital cost is selected in this analysis of storage technology. The capital cost in 2016 for lithium-ion battery and solar PV is used [179, 180].

5.2.5.2 Battery security

The dynamic vulnerability of sudden disturbances on battery will be here expressed by using both *DI curve* and *RI curve*, as one of the application examples of dynamic vulnerability in fuels, presented in Chapter 3.2. This analysis sets the number of options for the assessed trouble rate and duration as follows. It is assumed that the battery cell is composed of five low parallel circuits and this analysis assesses the trouble rate by 20%, which is used as input for the variable s. Following the trend of solar PV generation, the interval of trouble duration is set as 4 hr, which is used as input for the variable t.

To analyze battery security in a quantitative manner this analysis proposes the two indices dedicated for system security based on the relations identified above:

1. Total accepted failure duration throughout one-day.
2. Total accepted failure rate throughout one-day.

The concepts above are related to each of the plots obtained in through the methods detailed in the previous section. By calculating the "area under the curve" of these curves, using equations (1) and (2), the accepted failure duration at the different failure rate and the accepted failure rate at the different failure duration can be obtained.

$$Battery\ security_{DI_x} = \int_{00:00}^{24:00} f_x(t)dt \tag{5.10}$$

$$Battery\ security_{RI_y} = \int_{00:00}^{24:00} g_y(t)dt \tag{5.11}$$

Where, $f(t)$: DI curve, $g(t)$: RI curve, t: instant of failure, x: battery failure rate, y: battery failure duration

Finally, the accepted maximum component under the various failure rate and failure duration needs to be synthesized into a composite battery security index. Here, two indices based on DI curve and

RI curve are presented. Probability of magnitude and duration in battery failure occurrence would determine the weighting for each of rate options and of duration options. Given that their probabilities randomly vary depending on the custom service quality, location and instant of time, for simplicity, this analysis assigns the equal weight for each of rate options and of duration options. Each of accepted failure duration and accepted failure rate under the various options are respectively aggregated to obtain the security indices by using the technique of root mean square in the following equations.

$$Battery\ security_{DI} = \sqrt{\frac{\sum Battery\ security_{DI_x}{}^2}{X}} \tag{5.12}$$

$$X = \frac{100}{s} + 1 \tag{5.13}$$

$$Battery\ security_{RI} = \sqrt{\frac{\sum Battery\ security_{RI_y}{}^2}{Y}} \tag{5.14}$$

$$Y = \frac{24}{t} + 1 \tag{5.15}$$

Where, X: the number of assessed failure duration options, Y: the number of assessed failure rate options

As a result, each component associates with system security from the perspectives of failure rate and failure duration. The greater index corresponds to the stronger component of system security.

5.2.5.3 Data Envelopment analysis

To demonstrate the process of determining the capacity size in the standalone distributed systems under study, a comparison of the diverse systems is done using Data Envelopment Analysis (DEA). This comparison is based on capacity size of the distributed system and its associated security indices obtained in the previous section.

DEA is a mathematical method from the field of operations research developed to compare performance among several decision making units (DMU) [181], and the comparison is assessed in terms of efficiency for each DMU. One important advantage of DEA is that it can handle several indicators with diverse units. Indicators are introduced into the model as inputs or outputs based on the direction of its effect on the efficiency. A linear programming problem is generated with efficiency of the DMU under analysis subjected to the efficiencies of other DMUs and by solving for each DMU, the resulting efficiencies range from 0 to 100 percent for each DMU, which can be interpreted as a 'benchmark index' with respect to the best performing one. The general form of the model is shown in equation 7, where E_m is the efficiency of the m^{th} capacity size, v_i is the weight assigned to output y_i (outputs range from j to J, this last being the total number of outputs); u_i is the weight assigned to input x_i (inputs range from i to I, correspondingly I the total number of inputs); and the conditions $v_j \geq 0$ and $u_i \geq 0$ for weights to be natural numbers.

$$\begin{aligned}
&max\ \ E_m = \frac{(Outputs)_m}{(Inputs)_m} = \frac{\sum_{j=1}^{J}\left(v_j y_j\right)_m}{\sum_{i=1}^{I}(u_i x_i)_m} \\
&\text{subject to} \\
&0 \leq \frac{\sum_{j=1}^{J} v_{jm} y_{jn}}{\sum_{i=1}^{I} u_{im} x_{in}} \leq 1, \ \ n = 1, 2,,, N \\
&u_{im}, v_{jm} \geq 0, \qquad i = 1, 2,,, I, \qquad j = 1,2,,, J
\end{aligned} \tag{5.16}$$

In order to compare storage technology in standalone distributed systems, the specific DEA formulation is modelled through the relationship of the two battery security indices and the storage cost of the system. Both indices (accepted failure duration at different failure rates, and accepted failure rate at different failure durations) take the role of inputs given that the lower its magnitude the higher the effect on efficiency, whereas the cost takes the role of the output, given its opposite effect.

As a final note, the DEA formulation described above uses what is known in DEA related literature as the CCR DEA model [182]. Applied to this case study, this means that the comparative analysis assumes constant returns in the efficiency relation between cost and security. This is so as to set the most efficient benchmark in the least number of storage technology types possible, and not to assume specific details about the production function. This procedure is also applied in contemporary DEA literature [183].

5.3 Results of possible range of solar panel and battery capacity

Energy stored in battery at the previous day has to be extracted to deliver the power at night before the solar PV starts its operation in the morning. As such, the minimum required energy left in battery at 00:00 hour to continuously supply electricity before solar PV operation on this day is obtained corresponding to the various solar panel rate from 10% to 20%. The result is shown in Figure 5.3. Vertical and horizontal axis means the energy left in the battery at 00:00 hour and solar panel rate. Less covered solar panel requires the more energy left in the battery at 00:00 hour. The obtained minimum required energy left in battery is used as the initial input so that the model runs the simulation under the identical condition. Here, the identical condition is assumed to be the condition where there is no stored energy in the battery before starting to charge the power generated by solar PV.

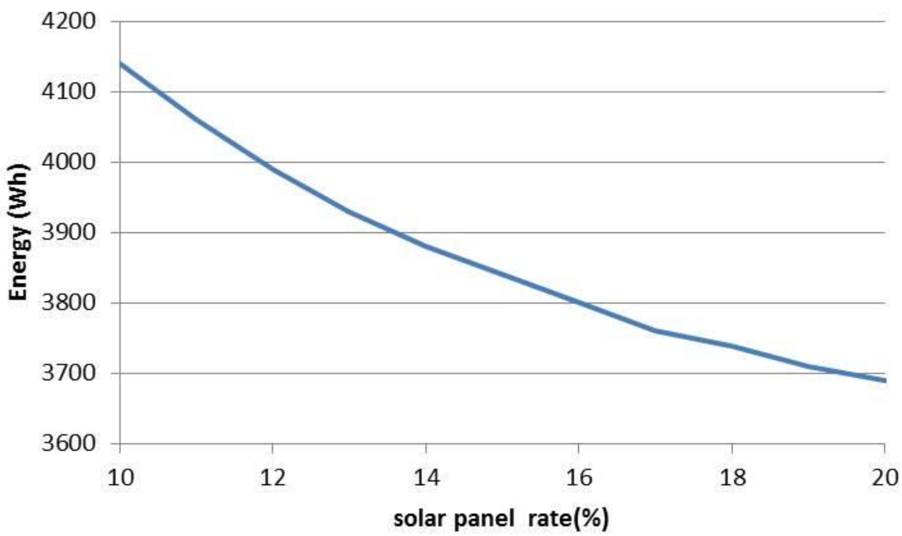

Figure 5.3 Minimum required energy left in battery

The minimum battery capacity under non-stoppage of PV operation is calculated corresponding to the different solar panel rate from 10% to 20%. The result is given in Figure 5.4. Vertical and horizontal axis means battery capacity and solar energy rate. Normally PV charge controller avoids the battery to be overcharged. When the battery is fully charged, the power generated by solar PV is not delivered to the battery. This minimum battery capacity under non-stoppage of PV operation can store the all of the surplus power. The battery capacity is increased in proportional to solar panel rate. The electricity consumption pattern is not changed in the case of battery capacity which is greater than the minimum battery capacity under non-stoppage of PV operation.

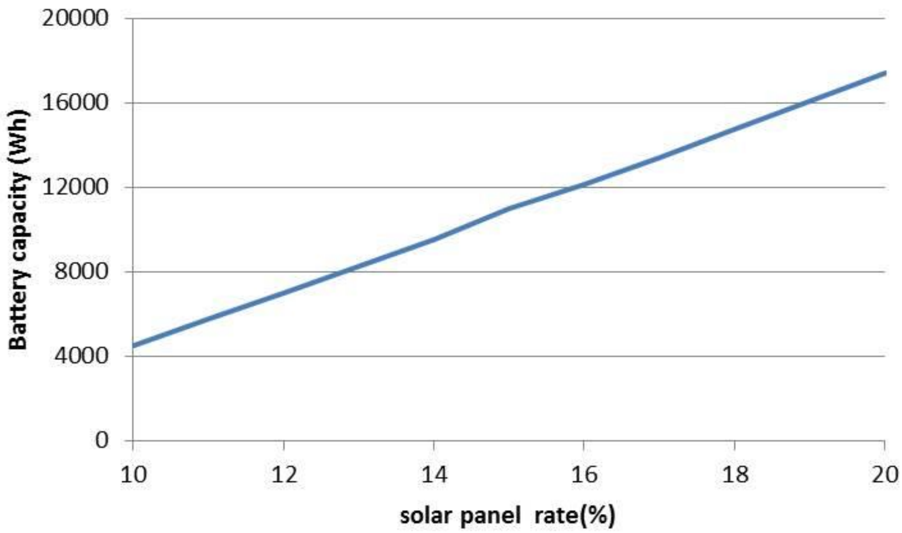

Figure 5.4 Minimum battery capacity under non-stoppage of PV operation

Subsequently, energy deficit in one-day is computed corresponding to the different solar panel rate under the minimum battery capacity under non-stoppage of PV operation. The result is given in Figure 5.5. The vertical and horizontal axis means energy deficit and solar panel rate. The energy deficit is gradually decreased with the solar panel rate increased. It can be observed that a minimum of 15% of solar panel rate is required to ensure the off-grid electricity system does not generate any energy deficit. As such, 15% of solar panel rate is identified as the minimum required solar panel rate. It must be mentioned that, under the sufficient solar panel rate installation, the energy left in the battery at 24:00 is greater than the minimum required energy left in battery at 0:00. This means non-energy deficit occurs at the following days under this input situation.

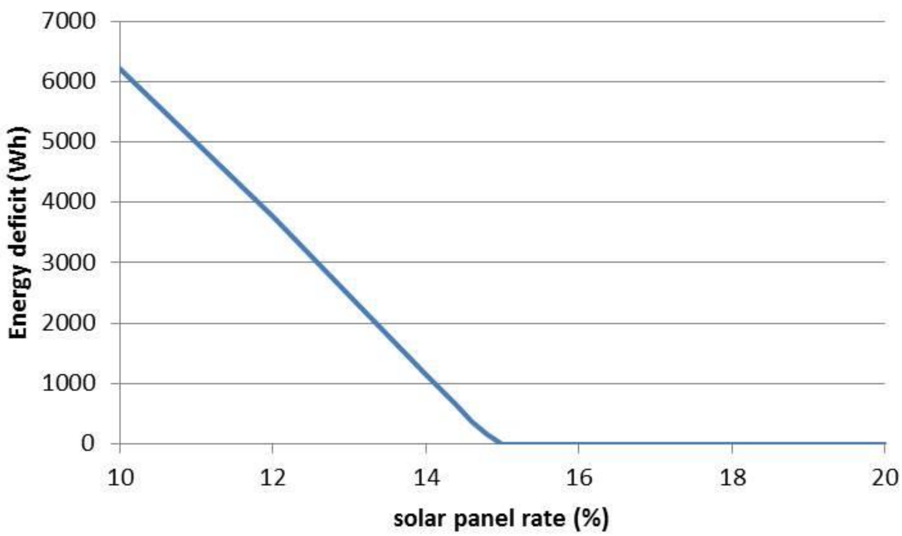

Figure 5.5 Energy deficit

The minimum battery capacity for non-disruption of electricity supply within a one-day snapshot assessed in this study is finally obtained. This condition is allowed to include the stoppage of solar PV operation. In this analysis, under the various solar panel rate which is greater than the identified minimum required solar panel rate of 15%, energy deficit is calculated changing the battery capacity. Like the aforementioned analysis on the energy deficit, the minimum required battery capacity is recorded where there is no energy deficit. The result is described in Figure 5.6. The vertical and horizontal axis means battery capacity and solar panel rate. The identified minimum required battery capacity for non-disruption of electricity supply remains almost the same, even though the solar panel rate increases. As such, 11000Wh is identified as the minimum required battery capacity. Assuming that the electricity capacity margin is 20% in this paper, the possible maximum installed capacity of both solar PV and battery is 18% and 13200Wh respectively.

As such, the analysis on the trade-off between system security and cost is conducted under the twelve combinations between battery capacity (11000Wh, 12000Wh and 13000Wh) and solar panel rate (15%, 16%, 17% and 18%).

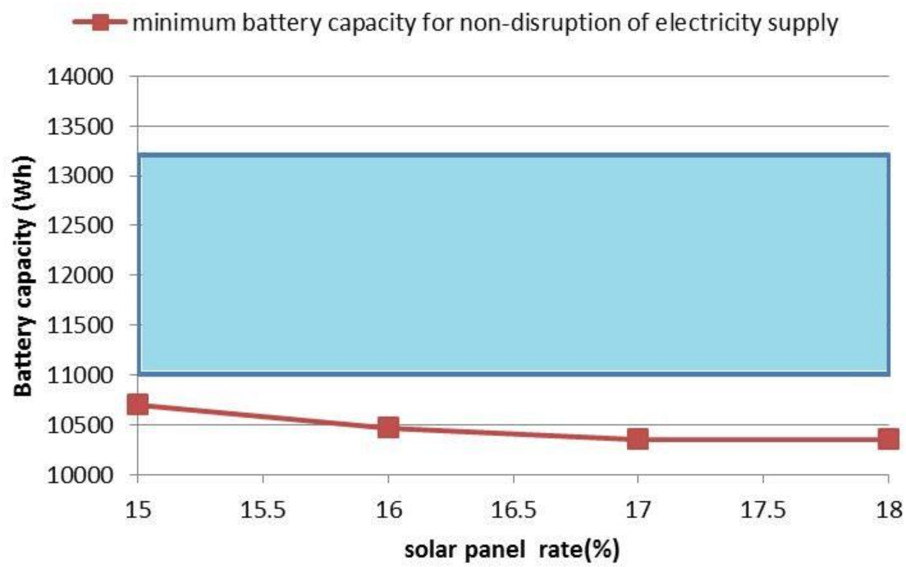

Figure 5.6 Possible range of covered solar panel and battery capacity within one-day snapshot

5.4 Results and discussion on the analysis for sudden disturbances on solar PV

5.4.1 Cost and solar PV security

The cost and solar PV security are quantified among the possible range of both solar panel rate and battery capacity.

The obtained DI curves under the various capacity combinations are shown in Figure 5.7. The vertical and horizontal axis means sustainable duration and instant of failure. The similar trend can be seen from all of the sustainable duration curves. Sustainable duration is gradually decreased with time until around 6:00 hour when the solar PV is supposed to start its operation. During day time, sustainable duration remains the same as zero. Subsequently, sustainable duration is increased dramatically after around 15:00 – 18:00 hour, which is here called time boundary. And then it is gradually decreased with time. The stored energy in the battery can supply the electricity in the following day if this magnitude of PV system failure occurs after evening. In the case of solar panel rate of both 16%, 17% and 18%, with the battery capacity increased the time boundary is shifted to the earlier time, which means the power security is improved from the perspective of instant of failure. In addition, the longer sustainable duration can be obtained under the more battery capacity. This DI curve can assist the system operator in making a proper action after the off-grid electricity supply failure.

The solar PV security of the off-grid electricity system is obtained by computing the area under the sustainable duration curve.

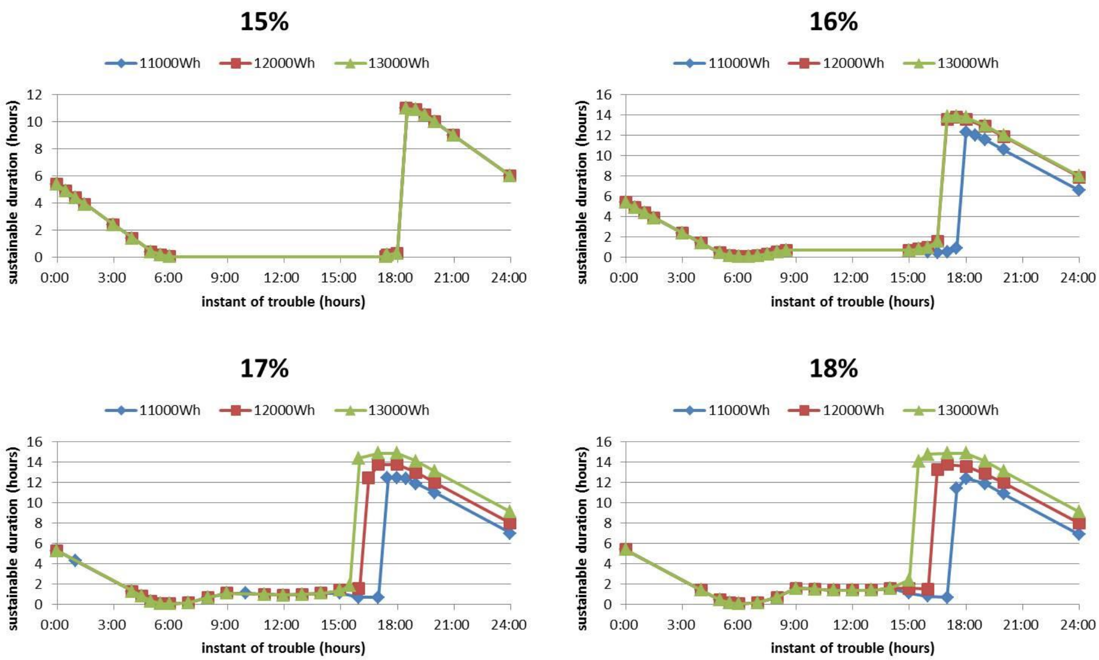

Figure 5.7 DI curve for solar PV failure under the different combinations

The cost (c_i) and solar PV security (s_i) is quantified grouping the same solar panel rate in Figure 5.8 and grouping the same battery capacity in Figure 5.9. The left and right vertical axis means cost and solar PV security, while the horizontal axis corresponds to the 12 combinations between solar panel rate and battery capacity. Here, the lower value of cost (c_i) and higher value of power security (s_i) correspond to the better choice.

Both cost and solar PV security follow the same trend under the same solar panel rate in Figure 5.8. In the case of 15% of solar panel rate, the value of both cost and solar PV security remains the same, because the given three options of battery capacity are greater than 11000Wh of the minimum battery capacity under non-stoppage of PV operation. It was mentioned above that the electricity consumption pattern remains the same with battery capacity being greater than the minimum battery capacity under non-stoppage of PV operation. In the case of 16% of solar panel rate, the cost increases while the solar PV security is strengthened with the battery capacity increased. It must be noted that the increasing rate of both cost and solar PV security is decreased in the case of the battery capacity difference between 11000Wh and 12000Wh compared to the case of the one between 12000Wh and 13000Wh. This is because the minimum battery capacity under non-stoppage of PV operation is 12130Wh. In the case of 17% and 18% of solar panel rate, both cost and solar PV security is increased in proportional to the increase in battery capacity.

On the other hand, under the same battery capacity, there is no similar trend between cost and solar PV security in Figure 5.9. Solar PV security is strengthened with solar panel rate increased, while cost might not have a specific trend through the different solar panel rate due to the non-consistent energy output pattern from both solar PV and battery.

In summary, the strengthened solar PV security by securing system redundancy can be quantitatively justified through the two group of solar panel rate and battery capacity.

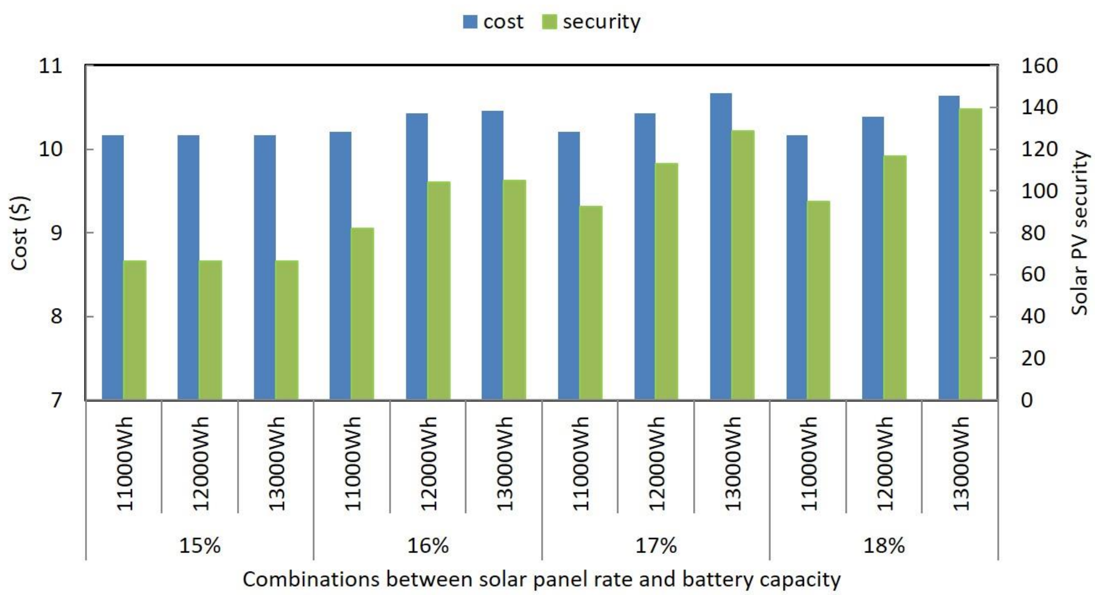

Figure 5.8 Cost and solar PV security based on the solar panel rate grouping

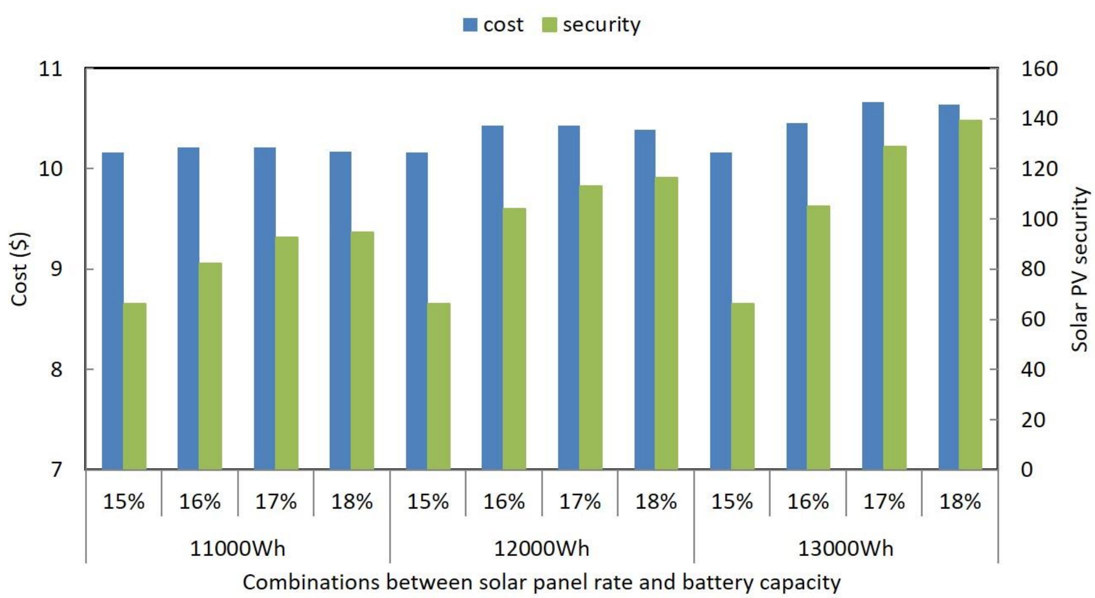

Figure 5.9 Cost and solar PV security based on the battery capacity grouping

5.4.2 Cost-security index

Cost-security index depends on how to weight the two indicators. The weighting of both cost and solar PV security might vary from other systems because of the various designed goals. The energy policy from economic and security perspective will contribute to the assignment of weighting factor [184]. While the weighting on each of the proposed indicators is subjectively determined, equal weight approach is commonly used as a reference case. In this section, following the equal weight approach, 0.5 is used as input for the weighting factor *x*. Cost-security index is obtained grouping the same solar panel rate in Figure 5.10 and grouping the same battery capacity in Figure 5.11. The vertical axis means cost-security index, while the horizontal axis means the 12 combinations between solar panel rate and battery capacity. The result of cost-security index is significantly affected by the result of each indicator. Lower cost-security index corresponds to the better design.

Based on the solar panel rate grouping, the trend of cost-security index with the change of battery capacity is similar. In the case of 15% of solar panel rate, the cost-security index remains the same regardless of the change of battery capacity, corresponding to the identical value of both cost and solar PV security. In the case of 16%, 17 %, and 18% of solar panel rate, the cost-security index is increased corresponding to the increment of battery capacity.

On the other hand, based on the battery capacity grouping, there is no similar trend of cost-security index with the change of solar panel rate. In the case of 11000Wh, the cost-security index is decreased with the solar panel rate increased. In the case of 12000Wh, the same score of cost-security index is obtained with both 15% and 16% of solar panel rate, and then the index is decreased when the solar panel rate is larger than 16%. Meanwhile, in the case of 13000Wh, the cost-security index is increased with solar panel rate increased up to 17%, on which cost has a significant influence.

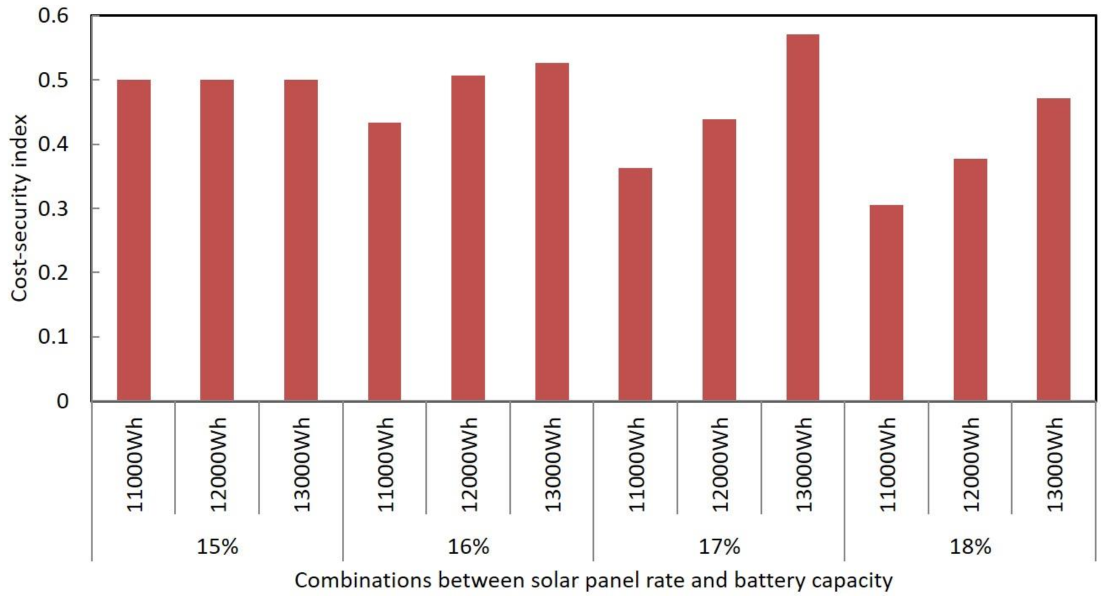

Figure 5.10 Cost-security index of the three weighting scenarios based on the solar panel rate grouping

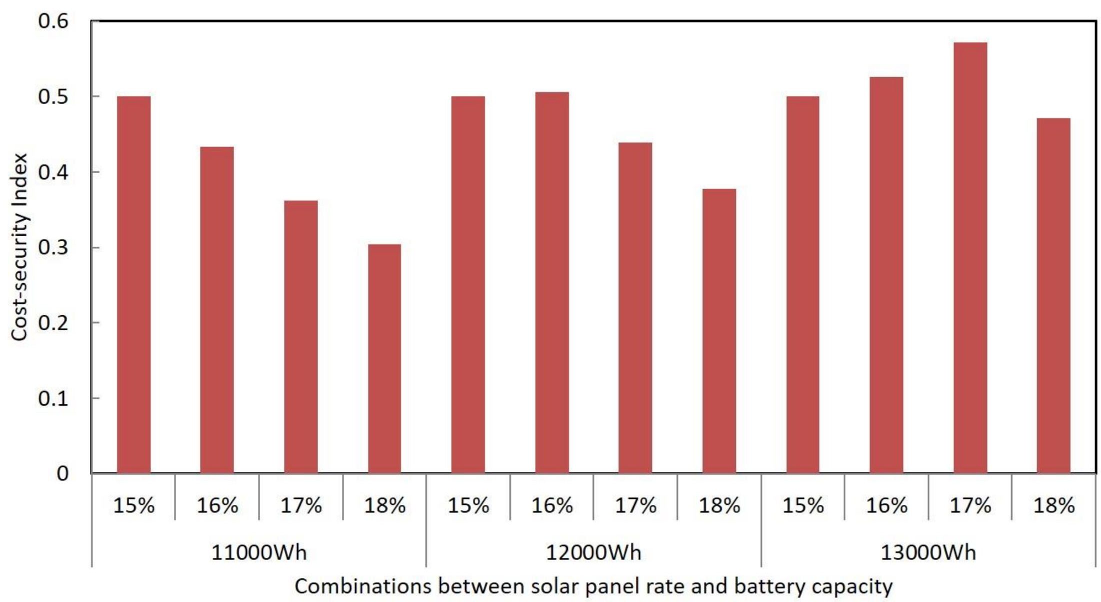

Figure 5.11 Cost-security index of the three weighting scenarios based on the battery capacity grouping

5.4.3 Sensitivity testing

The cost-security index has been quantified, which utilizes the equal weight on both cost and solar PV security. However, the aggregated index based on proposed indicators depends on the determination of weighting approach. Even though the equal weight is common approach, the weight of indicator is subjectively affected by the energy landscape. For example, easy access to the manufacture for the maintenance and repair of the system failure contribute to the allowance of sustainable duration, which can allow the system designer to pay less attention to the solar PV security aspect. Meanwhile, the energy-related cost of both renewable and storage technology would have a wide gap between the individual region reflecting the maturity of domestic markets, local labor and manufacturing costs and incentive levels [173], which differs the weight on cost compared with solar PV security among regions. Besides that, given that the energy landscape is highly expected to be changed in future, uncertainties of energy projection leads to the difficult determination of assigning the proper weighting on both cost and solar PV security. As such, the weighting factor is explored to analyze the impact of uncertainty on the cost-security index.

In order to analyze the uncertainties, sensitivity testing is conducted. Sensitivity testing of cost-security index is the process of changing the weighting factor. The action of changing the weight is repeated for many times so that a spread of output is obtained. Monte Carlo simulation, known as multivariate sensitivity simulation, allows this process to be conducted automatically. The weight factor x is changed in the way of random uniform distribution, where any number between zero and unity is equally likely to occur. 2000 times of simulations can be performed to provide the result of sensitivity with histograms.

Histograms display the number of simulations which are categorized in a given range of the cost-security index. The results of the twelve capacity combinations are given in Figure 5.12. The vertical axis means the number of simulations, while the horizontal axis means the obtained cost-security index separated into a given range. The yellow bar corresponds to the cost-security index based on the equal weight scenario, while the range of cost-security index corresponding to the largest number of simulations of each combination is named the highest sensitivity cost-security index. Subsequently, the gap between both cost-security index with the equal weight scenario and the highest sensitivity cost-security index is also obtained in the following equation:

$$\text{gap} = (x - 0.5)\big(\omega(z_{ci}) - \omega(z_{si})\big) \tag{5.17}$$

The results of cost-security index based on equal weight, the highest sensitivity cost-security index, and the gap are presented in Table 5.2.

The highest sensitivity cost-security index is the most likely to be obtained regardless with the weighting factor in regions where equal weight is not applied. Given that the lower value of cost-security index contributes to better performance, the capacity combination of both solar panel rate of 18% and battery capacity of 11000Wh can be considered as the most appropriate installation design within a one-day snapshot under the condition applied in this study.

System designers who applied equal weight for cost-security index are allowed to consider the impact of uncertainties of energy landscape. A negative gap means that the highest sensitivity cost-security index has a better performance than the cost-security index based on the equal weight scenario. In addition, the larger absolute gap under varying the capacity combination means that the equal weight scenario is considered vulnerable. It can be observed that the greater installation of both solar panel rate and battery capacity has a larger gap between the equal weight scenario and high sensitivity. The equal weight scenario in the case of 18% of solar panel rate as well as in the case of 11000Wh of battery capacity can be comparatively considered the most reliable within a one-day snapshot under the condition applied in this study.

The ambiguity of current energy landscape will cause the high uncertainties of future projection, leading to the difficult determination of assigning the proper weighting on both cost and solar PV security. Sensitivity testing would help to obtain the reliable information of cost-security index including the uncertainties of future energy landscape. The combination of cost-security index with sensitivity testing would be of use to the operator of off-grid electricity system in designing the capacity installation of both renewable energy and storage technology.

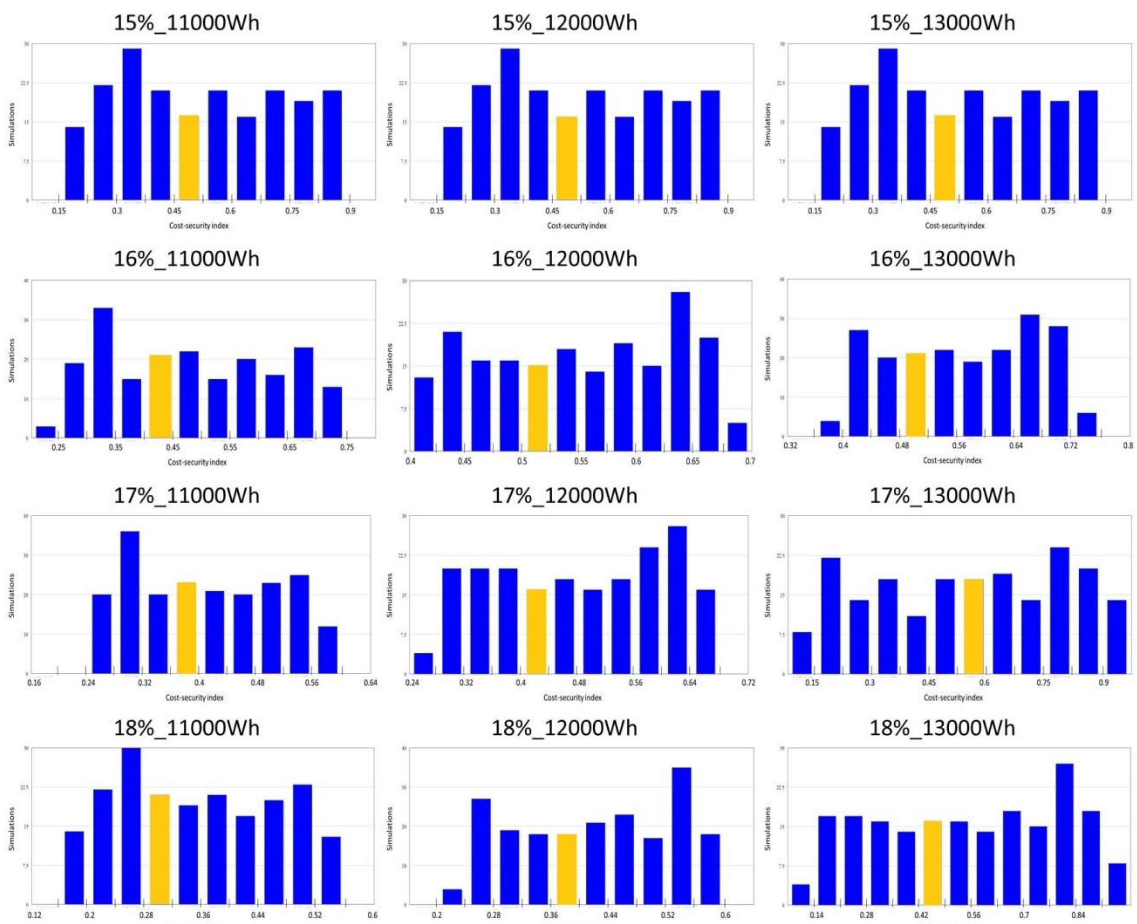

Figure 5.12 Sensitivity testing

Table 5.2 Analysis on uncertainties of weighting factor

Combinations		Equal weight	High sensitivity	Gap
15%	11000Wh	0.5	0.43	-0.07
	12000Wh	0.5	0.43	-0.07
	13000Wh	0.5	0.43	-0.07
16%	11000Wh	0.43	0.33	-0.1
	12000Wh	0.51	0.64	0.13
	13000Wh	0.53	0.66	0.13
17%	11000Wh	0.36	0.3	-0.06
	12000Wh	0.44	0.62	0.18
	13000Wh	0.57	0.79	0.22
18%	11000Wh	0.3	0.26	-0.04
	12000Wh	0.38	0.54	0.16
	13000Wh	0.47	0.8	0.33

5.5 Results and discussion on the analysis for sudden disturbances on battery

5.5.1 DI and RI curves

The construction of the two plots necessary to evaluate battery security yielded the DI curve and the RI curve.The features of this process, using 13000 Wh of battery capacity are demonstrated as the example.

First, the relationship between failure duration and instant of failure as seen through the DI curve (Figure 5.13) shows that, in general, greater failure rate observes less failure duration at any instant of failure. Based on this, the standalone electricity system will remain self-sufficient for a longer time with less rate of failure, regardless of when it takes place.

Another interesting finding is that there is similar trend for any failure rate. This trend is described by a sharp decrease in failure duration until the instant of failure becomes 15:00, when it can drastically increase for failure rates around 20%. If the failure rate is higher than 20% this point of overshoot is delayed of shifted. The point of overshoot called time boundary in this article, sets a threshold from where system security can significantly improve. The occurrence of time boundary is due to that the system could be self-sustained and sustainable duration could be consequently extended as long as the battery could store a certain amount of energy to be used until the start of solar PV operation. Except for 100% of failure rate, the time boundary is seen after 12:00 and with decreasing failure rate it is seen in earlier hours. As also seen in Figure 5.13, the time boundary observed for failure rates of approximately 80-100% would occur during the morning. In these cases, any single moment of battery failure causes the supply disruption before the time boundary.

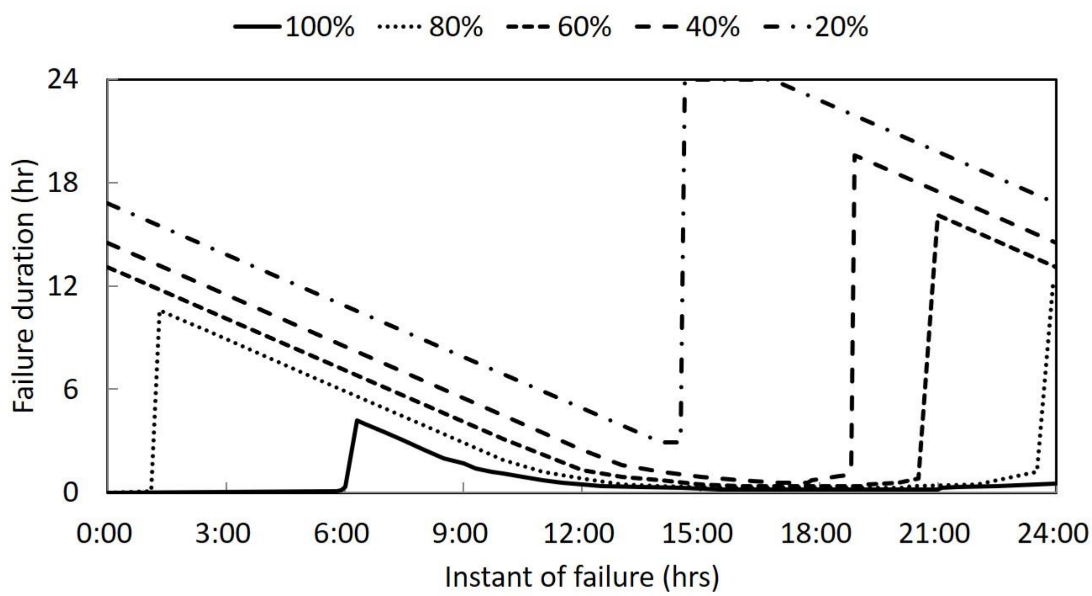

Figure 5.13 DI curve for battery failure in the case of 13000 Wh of battery capacity

The RI curve (Figure 5.14), in turn, shows that failure rate is higher with decreasing failure duration, regardless of the moment when the failure happens. Only in the case that failure rate is less than 19%, the standalone system remains self-sufficient at any failure duration.

It is noteworthy that the trend of this curve changes by length of failure duration. In the cases of 4 hr and 8 hr, the accepted failure rate increases with time. It starts declining after reaching their peaks of 100% for 4 hr and 80% for 8 hours at approximately 4:00 and 7:00 am correspondingly. A minimum of 20% of failure rate is reached at 9:00 am for 4 hr and at 13:00 for 4 hr, and there both remain until 16:00 when their accepted failure rates increase again until they reach again their peaks in the next cycle. On the other hand, in the cases of 12 hr and 16 hr of failure duration, the accepted failure rate declines to 20% before 6:00, but rises again up to lower maximums than the other two cases until 16:00 as well. Additionally, in the cases of 16 hours, 20 hr and 24 hr, the accepted failure rate remains at 20% until 15:00. It then gradually increases, but shortly after it declines.

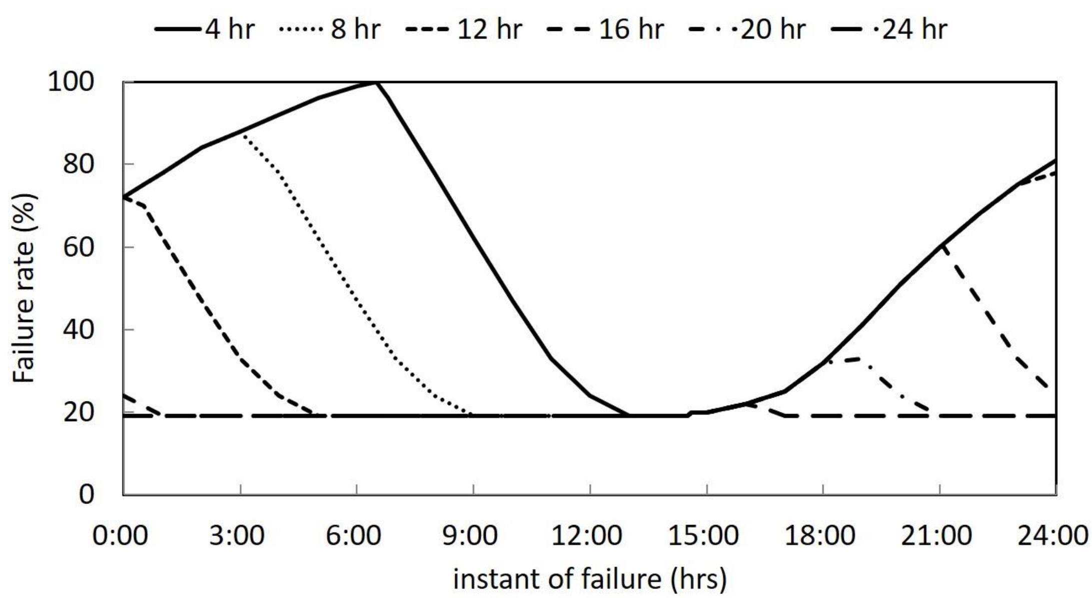

Figure 5.14 RI curve for battery failure in the case of 13000 Wh of battery capacity

Based on Figure 5.13 and Figure 5.14, it could be said that, under duration when solar PV operates, the system is more vulnerable after the peak around 12:00 than before the peak, and also that the security of electricity power system for the battery failure during periods when battery charges surplus power is more vulnerable compared with periods when battery is operated. The availability of DI and RI curve could be of use to implementers in examining countermeasures for the sudden failures of battery facilities and making wiser decisions in the customer services.

5.5.2 Evaluation of battery security

The relationship between failure duration, instant of failure and failure rate are the constituents of the quantitative analysis of battery security proposed in this study. For each component, the integrals of the DI (failure duration) and RI (failure rate) curves outlined in the previous section are presented in Figure 5.15.

From the plots in Figure 5.15 it is observed that battery security on a basis of DI curve decreases with increasing failure rate and it is improved with increasing battery capacity. Under 0% of failure rate, 576 points are obtained, which is a maximum value of battery security_{DI} regardless with battery capacity. Meanwhile under 100% of failure rate, battery security_{DI} is indicated in the range between 13.3 and 16.5 without any significant difference, which is a minimum value. In other word, the state of being exposed to the risk of 100% failures of battery operation presents merely 2% of maximum battery security in the power system compared with the case of no failure on the facilities.

Each of battery capacities have a certain magnitude of failure rate, under which the power disruption is not caused. Here it is named an accepted failure rate, given in Figure 5.16. Among the assessed battery capacity, the accepted failure rate linearly increases with increasing battery capacity. Due to this trend, at 20% of failure rate the power system with more than 13500 Wh reaches the maximum security. Up to the accepted failure rate, battery security$_{DI}$ linearly increases with decreasing failure rate.

From the plots in Figure 5.15 it is observed that battery security on a basis of RI curve decreases with increasing failure duration and it is improved with increasing battery capacity. Under 0% of failure rate, 2400 points are obtained, which is a maximum value of battery security$_{RI}$ regardless with battery capacity. Meanwhile under 24 hrs of failure duration, battery security$_{RI}$ is indicated in the range between 0 and 724, which is a minimum value for each of battery capacities. Among the assessed battery capacity options, the minimum value of battery security$_{RI}$ linearly increases. In other word, the state of being exposed to the risk of 24 hrs failures of battery operation presents 0% of maximum battery security in the power system compared with the case of no failure on the facilities under 10500Wh as the minimum battery capacity. On the other hand, it presents 30% of maximum battery security under 15000Wh as the maximum battery capacity. In contrast to battery security$_{DI}$, it would appear that battery security$_{RI}$ increases with decreasing failure duration in an exponential manner.

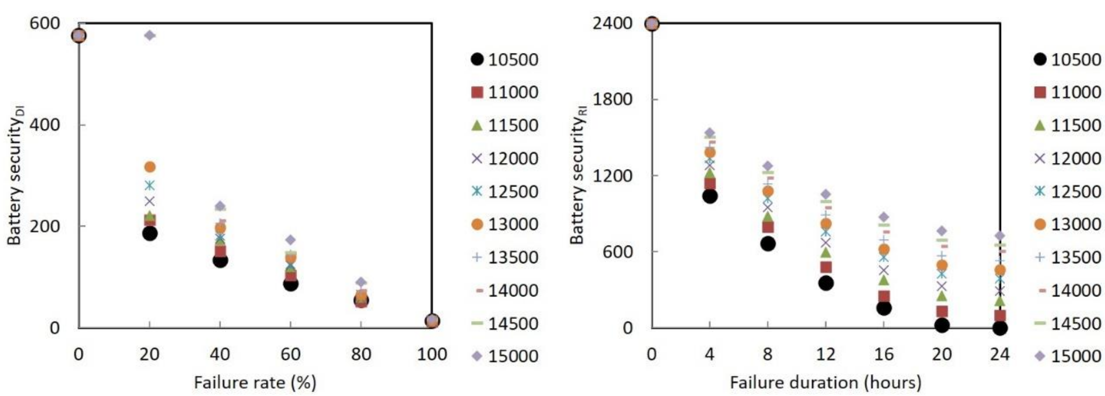

Figure 5.15 Components of system security in a sudden contingency of the battery system in a standalone power system

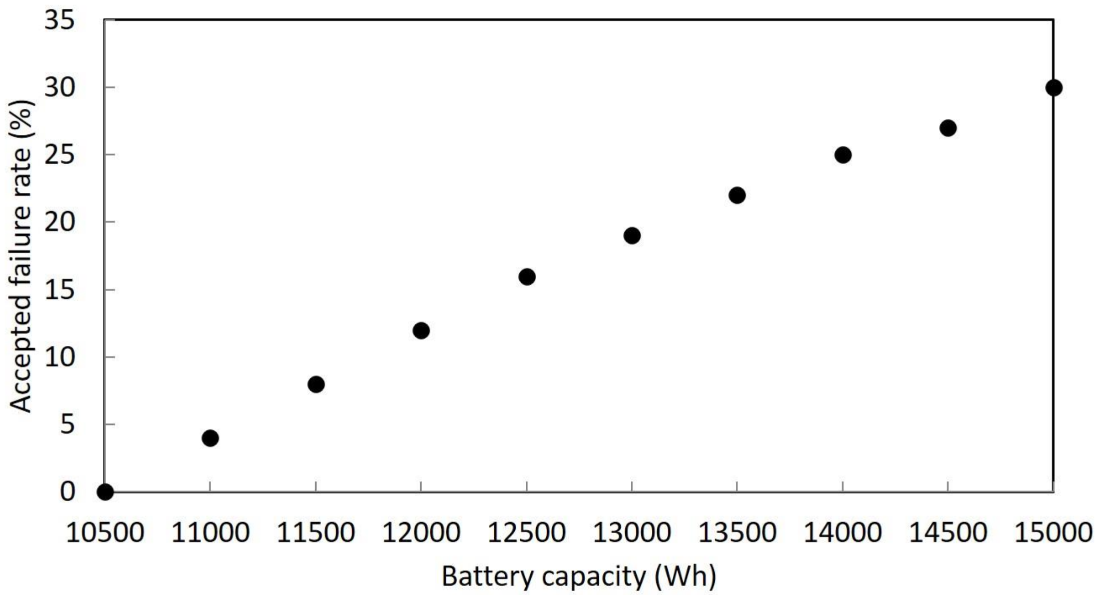

Figure 5.16 Accepted failure rate under the different battery capacity

The two indices for the overall battery security on DI curve and RI curve are obtained. The result is presented in Figure 5.17. Both indices almost linearly increase with increasing battery capacity. As for overall battery security$_{DI}$, the significant gap between 13000 Wh and 13500 Wh of battery capacity is caused by the differences of accepted failure rate presented in Figure 5.16.

The overall battery security$_{DI}$ is illustrated in the range 250-350, while the overall battery security$_{RI}$ is illustrated in the range 1000-1350. Given the maximum battery security$_{DI}$ and battery security$_{RI}$ are 576 and 2400, the normalized overall battery security$_{DI}$ and the normalized overall battery security$_{RI}$ are computed, presented in Table 5.3. Even for 10500 Wh of required minimum battery capacity, more than 40 % of maximum security could be contained in the developed method. And then, 15000 Wh of battery capacity with 42.9% of capacity margin delivers 1.39 times in the overall battery security$_{DI}$ and 1.31 times in the overall battery security$_{RI}$ greater than 10500 Wh of required minimum battery capacity. In other words, it could be possibly said that the incremental rate of battery security would be less than the incremental rate of capacity margin.

Setting the boundary of security would be useful to assist in designing the capacity size. The boundary might vary depending on the probability of disastrous event occurrence, battery component structure, the custom service quality, the installation location, and political and ideological implications. For example, given that the reserve margin in 2014 in Japan was 16.6% [185], 48.2% for the normalized overall battery security$_{DI}$ and 47.2% for the normalized overall battery security$_{RI}$ could be considered as a reference case of power system security in Japan. The reference case determined on a basis of current situation in each of countries would lead to the future security boundary covering the incremental risk of natural disasters arising from climate change.

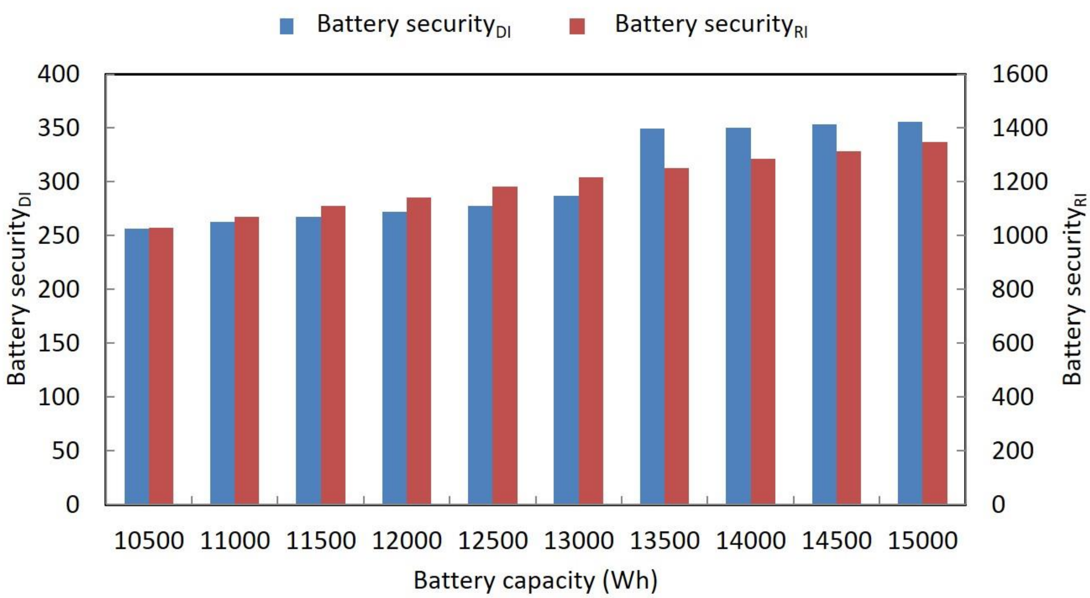

Figure 5.17 Overall battery security of power system under the different battery capacity

Table 5.3 Rate of overall security indices over the maximum security

Battery capacity (Wh)	Normalized battery security$_{DI}$ (%)	Normalized battery security$_{RI}$ (%)
10500	44.6	42.9
11000	45.6	44.6
11500	46.4	46.3
12000	47.2	47.6
12500	48.2	49.2
13000	49.9	50.7
13500	60.6	52.1
14000	60.8	53.6
14500	61.3	54.8
15000	61.8	56.2

5.5.3 Evaluation of DEA

Following the DEA-based procedure, it was found that in general, larger battery capacities provide a better battery security score, being best performers those in the range of 13,500 to 15,000 Wh and worse ones those in 10,500-11,500 Wh.

Based on the results of DI and RI curves, multiple cross sections represent diverse failure rates and failure durations within each figure, and such information had to be integrated to retrieve each system security index introduced in the DEA model. To provide a wider perspective the integration had to consider diverse battery security index results; a range that started from a minimum rate, corresponding to the case where a largest area above the curve was found, and several mean values that considered all the curves using different methods: Harmonic Mean (HM), Geometric Mean

(GM), Arithmetic Mean (AM), and Root-Mean Square (RMS). Table 5.4, Table 5.5, and Table 5.6 presents the efficiency results of the DEA estimations.

From Table 5.4, we observe that security-to-cost efficiency of the system (considering both indices) mostly increase with a raise in storage capacity, albeit some noteworthy cases. First of all, systems with 11,000 and 12,000 Wh storage capacities seem to be slightly outperformed by the smaller 10,500 and 11,500 Wh type when focusing on the most critical battery security values (minimum and HM scores). The same could be said for the 14,500 Wh system, which could arguably be considered as good in performance as the 15,000 Wh type. Among systems in the mid-range of efficiency, the same holds for 12,500 Wh battery, which seems in fact a better performer than the 13,000 Wh one. Yet, we should keep in mind that all these assertions are based on the most critical values, because as the aggregation of battery security indices increase in magnitude from using alternative mean estimation methods, the correlation between efficiency and capacity is more clearly demonstrated.

Consistent with the general outcome, DEA models for each battery security index with cost assessed separately (Table 5.5 and Table 5.6) support the overall finding. Progressive increase in the efficiency correlates with larger capacity. Yet, solely looking at each battery security index does not favour the cases of some smaller-capacity batteries outperforming their consecutive larger one, as attested and explained above through the analysis of the DEA model considering both indicators.

In sum, through the DEA outcomes in this section we can conclude that as a general rule larger battery capacities provide higher battery security, but for the most critical situation some particular types can be as or even somewhat more efficient than the immediate larger types in the list considering both failure rate and failure duration.

Table 5.4 DEA results (failure rate (DI), failure duration (RI), and capital cost)

capacity [Wh]	Min	HM	GM	AM	RMS
10500	87.5%	78.5%	65.6%	69.3%	84.1%
11000	84.4%	78.1%	68.8%	72.2%	86.4%
11500	86.7%	82.6%	74.0%	75.0%	88.6%
12000	83.3%	80.2%	74.2%	78.7%	90.3%
12500	94.4%	89.1%	78.8%	84.1%	92.4%
13000	92.3%	89.1%	82.2%	87.8%	94.1%
13500	96.3%	94.2%	92.9%	98.0%	100.0%
14000	98.6%	96.1%	93.6%	97.6%	99.7%
14500	100.0%	100.0%	97.9%	99.1%	99.9%
15000	100.0%	100.0%	100.0%	100.0%	100.0%

Table 5.5 DEA results (failure rate (DI) and capital cost)

capacity [Wh]	Min	HM	GM	AM	RMS
10500	87.5%	78.5%	65.6%	69.3%	78.4%
11000	84.4%	78.1%	68.8%	72.2%	79.3%
11500	86.7%	82.6%	74.0%	75.0%	79.9%
12000	83.3%	80.2%	74.2%	76.1%	80.3%
12500	94.4%	89.1%	78.8%	78.3%	81.2%
13000	92.3%	89.1%	82.2%	81.7%	83.1%
13500	96.3%	94.2%	92.9%	98.0%	100.0%
14000	98.6%	96.1%	93.6%	97.6%	99.2%
14500	100.0%	100.0%	97.9%	99.1%	99.1%
15000	98.4%	100.0%	100.0%	100.0%	98.8%

Table 5.6 DEA results (failure duration (RI) and capital cost)

capacity [Wh]	Min	HM	GM	AM	RMS
10500	0.0%	0.0%	5.5%	59.2%	84.1%
11000	14.4%	27.2%	42.6%	66.9%	86.4%
11500	31.3%	46.2%	57.7%	74.1%	88.6%
12000	42.8%	57.0%	66.2%	78.7%	90.3%
12500	56.3%	68.6%	75.3%	84.1%	92.4%
13000	66.2%	76.3%	81.4%	87.8%	94.1%
13500	75.8%	83.4%	86.9%	91.3%	95.7%
14000	85.1%	90.1%	92.1%	94.8%	97.3%
14500	91.1%	94.4%	95.6%	97.1%	98.5%
15000	100.0%	100.0%	100.0%	100.0%	100.0%

5.6 Conclusion

This Chapter first proposed the methodology of analyzing system security in response to sudden disturbances of both solar PV and battery system in the fictitious distributed system within a one-day snapshot adopted as an assessed time range of this study. System security was defined as the ability of electricity system to remain self-sufficient after the occurrence of sudden disruptions on the basis of the concept of dynamic vulnerability. The relationship between failure duration and instant of failure and between failure rate and instant of failure was identified by changing the three major parameters associated with sudden disturbances. And then, the system security index dedicated for the sudden disturbances of solar PV and battery failure was individually proposed in a quantitative way. Finally, from the perspectives of the developed security indices and cost, the process of determining capacity size was demonstrated through cost-effectiveness analysis.

In the assessment of sudden disturbances on solar PV, it has been discovered that, taking into account the impact of uncertainties of weighting factor, the capacity combination of both solar panel rate of 18% and battery capacity of 11000Wh can be considered as the most appropriate installation design within a one-day snapshot adopted as an assessed time range of this study.
In the assessment of sudden disturbances on storage technology, it was discovered that system security declines with increasing failure rate and failure duration in the downward-convex exponential manner. In addition, under duration when solar PV operates, system security is more vulnerable after the peak around 12:00 than before the peak. Furthermore, the fictitious distributed system for the battery failure during periods when battery charges surplus power is more vulnerable compared with periods when battery is operated. Through a DEA-based comparison of storage technology, in general larger storage capacity provides higher system security, but in the most critical situations some particular types can be as or even marginally more resilient than the immediate larger types, considering both failure rate and failure duration.

In summary, the established methodology can be considered as a promising approach to determine the capacity combination from cost and security perspective including the uncertainties of future energy landscape. Besides the fact that this research focuses on the off-grid house scale, this algorithm can be applied to the larger scale of off-grid electric system such as rural electrification covering the different weighting factor. This Chapter examined sudden disturbances of solar PV and battery in the distributed network as a case study of application of developed methodology for dynamic vulnerability in energy security. Sub-Q3 and sub-Q4 have been addressed under the case of distributed network.

CHAPTER 6 : Comparison between dynamic and static vulnerability

6.1 Introduction

The dynamic vulnerability in the context of diversity in power mix has been conceptualized in Chapter 3 (corresponding to sub-Q.1). Then, a method for analyzing the dynamic vulnerability of the power system considering sudden disturbances on a power source has been developed (corresponding to sub-Q.2). This method has been applied into two case studies of sudden disturbances on a particular power source in centralized network and distributed networks to develop an index dedicated for the dynamic vulnerability associated with specific power sources (corresponding to sub-Q.3) and to demonstrate the process of determining capacity size with considering the concept of system security (corresponding to sub-Q.4).

Extending the subject of power sources from one particular to all components and synthesizing the methods used for both centralized and distributed network, finally, the difference of the trend between the static vulnerability conventionally employed and the dynamic vulnerability newly addressed in the context of diversity in power mix will be analyzed to address the central question.

This Chapter is structured as follows: Chapter 6.2 explains the methodology for the quantification of the dynamic vulnerability. Chapter 6.3 presents the case studies including the distributed network and the centralized network. Chapter 6.4 demonstrates the comparison of static and dynamic vulnerability under the case studies. Chapter 6.5 extracts the implications from the obtained results, discusses the limitation of this study by interpreting the concept of diversity, and concludes this Chapter.

6.2 Methodology

The potential risk of supply disruption depends on the physical supply capability determined under the dynamic condition of balance between demand and supply at a certain time. Therefore, vulnerability is based upon supply capability while avoiding supply disruptions and analyzing the supply capability at a given time highlights the dynamic change in potential vulnerability inherent in the electricity systems.

The supply capability reflects a fundamental aspect of the ability of the system to withstand failures of power source components and to remain self-sufficient. The state of self-sufficiency depends on the magnitude and duration of failures. The system remains self-sufficient within the maximum accepted magnitude and duration of failures. In other words, the combination of the greatest accepted magnitude of failure and the longest accepted duration of failure at a given instant leads to an electricity system with the most resilient supply capability at an arbitrary time. As such, the dynamic vulnerability of sudden disturbances on power will be here expressed by using *DR curve*, as one of the application examples of dynamic vulnerability, presented in Chapter 3.2.

Next, based on the DR curve with the threshold of failure rate and duration taking sudden disturbances into account, the index dedicated for the dynamic vulnerability was developed. Given that the power system remains self-sufficient even after the occurrence of sudden disturbances within the threshold, it could be said that the area under the DR curve would represent the security of power system. By calculating the area under the curve, the security of power system against sudden disturbances on each of power sources at the assessed instant of time is obtained in the following equation.

$$SR_z = \int_{0\%}^{100\%} y_z(x)dx \tag{6.1}$$

Where, SR_z is the security of power system at the assessed instant of time (*z*), $y_z(x)$ is the magnitude-duration curve, *z* is the instant of sudden disturbance occurrence, and *x* is the failure rate.

Then, the relationship between security and vulnerability is exhibited in Figure 6.1. The boundary is indicated as the DR curve. Considering the maximum security of power system, the degree of dynamic vulnerability in the power system at the assessed instant of time is expressed in the following equation.

$$V_z = \frac{SR_{max} - SR_z}{SR_{max}} \times 100\ (\%) \tag{6.2}$$

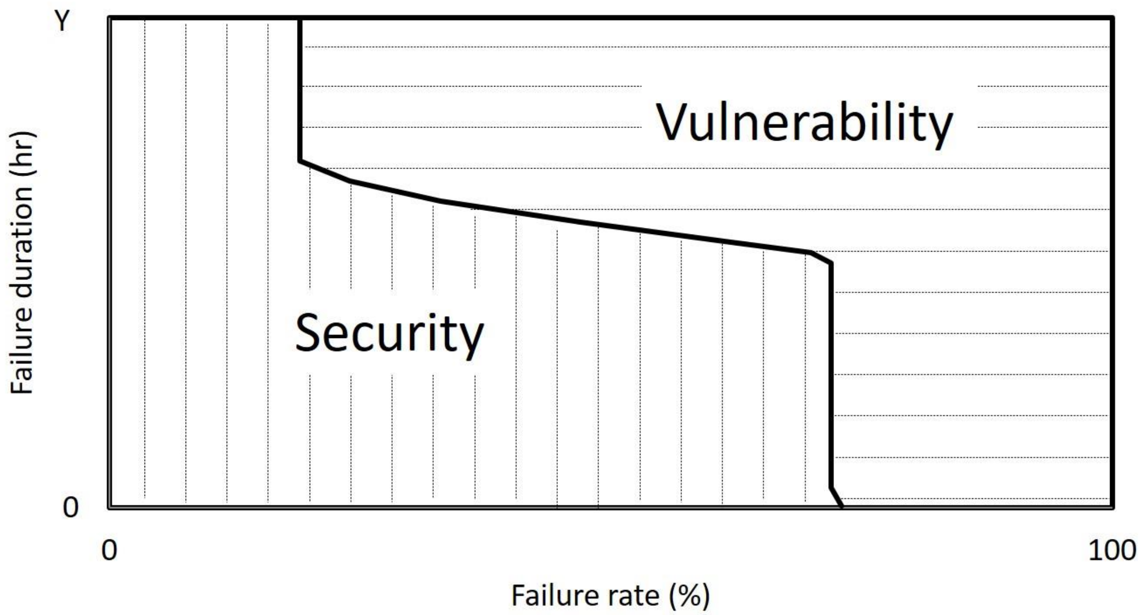

Figure 6.1 Relationship between security and vulnerability based on the magnitude-duration curve

In order to synthesize the obtained degree of vulnerability in the power system at the each assessed instant of time into an index for a dynamic vulnerability of power system to disruption of continuous power supply due to sudden disturbances, the plots are connected as presented in Figure 6.2. The dynamic vulnerability is presented in the following equation:

$$STV = \frac{\int_{00:00}^{Z} V(z)dz}{\int_{00:00}^{Z} 100dz} \times 100\ (\%) \tag{6.3}$$

Where, *DVI* is the dynamic vulnerability for a specific power source, *Z* is the end of assessed instant of time, $V(z)$ is the function generated by connecting each plot of the degree of vulnerability at the each assessed instant of time. The greater *DVI* corresponds to a more vulnerable power system against sudden disturbances.

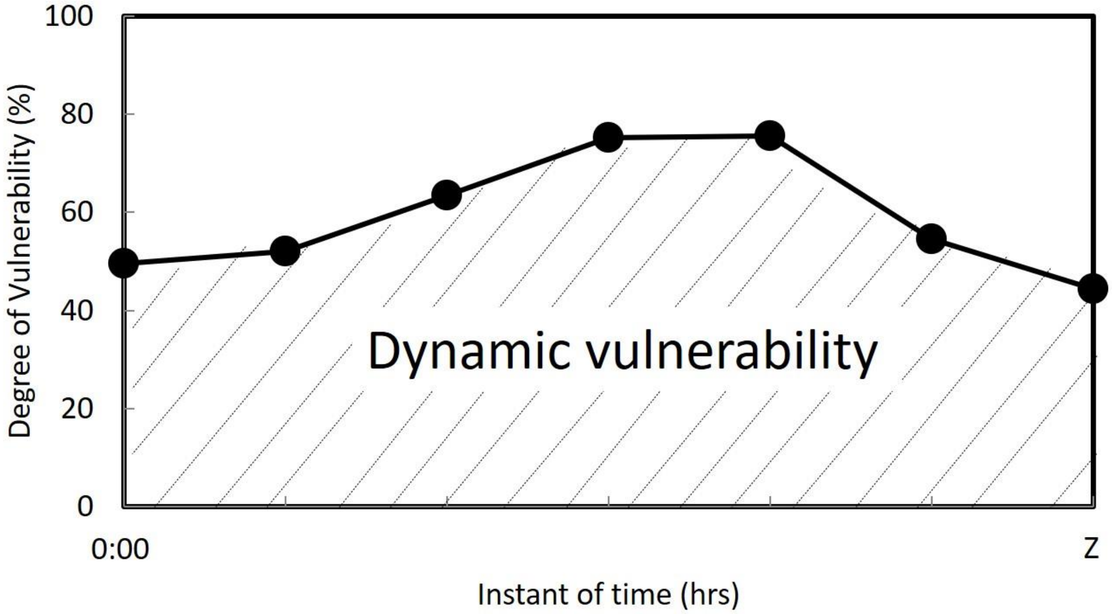

Figure 6.2 Quantitative concept of dynamic vulnerability

Finally, following the conventional manner, the static vulnerability is obtained by calculating energy generation by each of energy sources during the periods from 00:00 to the end of assessed instant of time.

6.3 Case studies

In this study, the range of time under consideration is one day (*Z*=24 hrs), and the instant of time when sudden disturbances occur changes from 00:00 up to 24:00 in 4-hour steps. Certain capacities of solar PV and battery are used as input under the condition where sufficiency is secured during one day. As previously mentioned, the maximum daily demand load profile of Japan is used in both distributed network and centralized network. The load profile is assumed to remain the same as the reference even after the occurrence of sudden disturbances, although in reality the electricity consumption is highly expected to decrease under such situation. Since this study utilizes the most severe daily load profile and retains its load profile even after the occurrence of sudden disturbances, the obtained results of dynamic vulnerability would be considered as the worst case in terms of shocks.

6.3.1 Centralized network

Centralized network is a conventional utility power system grid. This study adopts the power demand and supply model in the fictitious centralized network developed in Chapter 4. The electricity flow of centralized generation in a standalone utility power system is modelled by using system dynamics software VENSIM, as shown in Figure 6.3. The fictitious centralized electricity network used in this study consists of base load facilities (e.g. hydro, nuclear, and coal), middle and peak load facilities (e.g. oil, liquefied natural gas (LNG)) and storage technology facility (e.g. pumped-storage hydro). The notable assumptions in this model are 1) operation of middle and peak load and pumped storage hydro could instantly response, while the output of load base is constant, 2) pumped storage hydro starts its operation when the power generation from LNG and oil reaches their maximum operation, and 3) amount of pumped-up water used for pumped-storage hydro is unlimited. The reference input power capacity of the fictitious centralized network is 3320, 9760, 1800, 6220, 8010, and 4880 MW for hydro, nuclear, coal, oil, LNG and pumped storage hydro, respectively), as presented in Table 4.2. Six different power capacity combinations are analyzed in this study by changing the nuclear capacity from 100% to 50% with decreasing by 10% to consider the sudden stoppage of nuclear, while the capacities of the other sources remain the same.

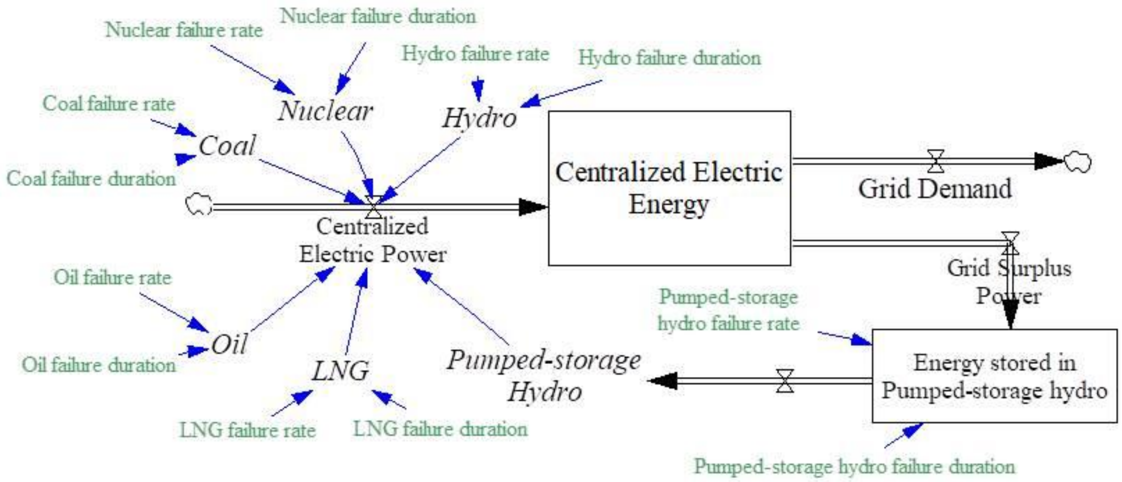

Figure 6.3 Electricity demand and supply model in the fictitious standalone centralized network (based on Chapter 4)

6.3.2 Distributed network

Distributed generation is defined from the perspectives of location and capacity [118]. It is directly connected on customer side of on-site meter or to utility grid at the distribution-level voltages [119, 120, 121]. Its capacity mostly ranges from less than a kW to tens of MW [122, 123]. As one of the forms in the distributed network, this study focuses on the hybrid renewable energy (solar photovoltaic (PV)) and battery system in an imaginary standalone house. Power demand and supply in a standalone house requires the smallest and simplest distributed system.

This study adopts the electricity flow of distributed generation in a standalone house based on Chapter 5. The electricity flow of distributed generation in a standalone house is modelled by using system dynamics software VENSIM, as shown in Figure 6.4. Solar PV acts as the distributed renewable energy source while the battery represents the storage technology. It is assumed that the output of solar PV is controlled under the case where battery is fully charged. The failure rate and failure duration for solar PV and battery is integrated in the model as a main parameter for the assessment of dynamic vulnerability. Referring to the result in Chapter 5, this study conducts the assessment for dynamic vulnerability for nine different combinations between solar panel rate (e.g. the rate of solar panel area to the roof-top area) and battery capacity as follows: (15%, 11000Wh), (15%, 13000Wh), (15%, 15000Wh), (18%, 11000Wh), (18%, 13000Wh), (18%, 15000Wh), (21%, 11000Wh), (21%, 13000Wh), and (21%, 15000Wh), which can achieve sufficiency within a one-day snapshot adopted as an assessed time range.

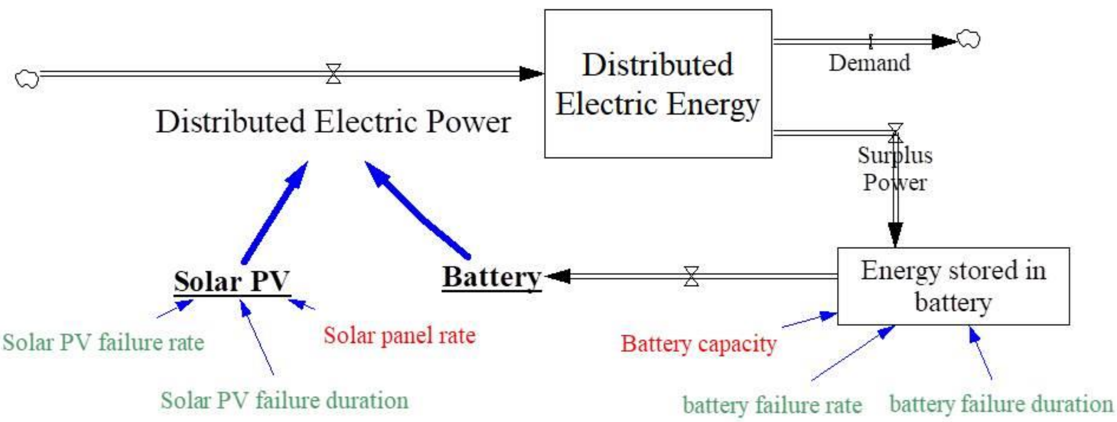

Figure 6.4 Electricity flow of distributed generation in a standalone house (based on Chapter 5)

6.4 Results

6.4.1 Centralized network

The degree of dynamic vulnerability at the assessed instant of time in the centralized network is presented in Figure 6.5.

In general, the transition of dynamic vulnerability for each power source with time exhibits the same trend; the degree of vulnerability increases from 00:00 until 08:00 and then remains almost the same until 16:00, and declines up to 24:00 after then. As this trend matches the daily demand curve, the peak time for demand around noon is the most vulnerable time in the centralized system for each of power sources. The trends for hydro, coal and pumped-storage hydro must be further noted. In the present model, the minimum surplus energy is generated by controlling the operation rate of oil and LNG early in the morning. For hydro and coal the degree of vulnerability in the range of 08:00-16:00 is extremely high, whereas their vulnerability is insignificant in other time range, which could be attributed to the insufficient energy stored in pumped-storage hydro. Despite its low capacity size, hydro and coal are highly sensitive at this time range (e.g. 08:00-16:00) to disruption of power supply. On the other hand, such extremely high degree of vulnerability in the range of 08:00-16:00 is not observed for pumped-storage hydro. This is because the failure of pumped-storage hydro in this time range affects its generation capacity and it still has significant reserve margin (e.g., 30% of reserve margin for pumped-storage hydro under the case of nuclear capacity of 60%). Thus, the availability of reserve margin in the pumped-storage hydro could contribute to the decrease in the degree of vulnerability at this time range, regardless of the amount of stored energy. Meanwhile, vulnerability in other time ranges (e.g. 0:00-4:00 and 16:00-24:00) is relatively high, which could be attributed to the restricted amount of water pumped up, leading to less amount of stored energy available to be used in the peak time.

Using the thus obtained degree of dynamic vulnerability at the assessed instant of time for the centralized network, the energy generation (static vulnerability) and dynamic (short-term) vulnerability by electricity source is obtained. The result is presented in Figure 6.6.

As the static vulnerability, energy generation of hydro and coal remains the same in the assessed capacity options, whereas the trend between nuclear and oil & LNG depends on the nuclear capacity size. For nuclear capacity of 100%, energy generation from nuclear is greater than that from oil & LNG. Then, with decreasing nuclear capacity, energy generation from oil & LNG increases and surpasses that from nuclear under less than 80% of nuclear capacity. Under the lower nuclear capacity (70, 60, and 50%) cases, pumped-storage hydro needs to be operated at the peak time.

As the dynamic vulnerability, the DVI value increases in the order of pumped-storage hydro, coal, hydro, nuclear and oil & LNG in all capacity combinations assessed in this study. The DVI value of each power sources increases with decreasing nuclear capacity. It must be noted that under higher nuclear capacity, DVI values of hydro, coal and pumped-storage hydro are even zero since the sudden full loss of these facilities could be covered by the controllability of oil & LNG.

The comparison of vulnerability between long- and short-term is found to exhibit a notably different trend. Under high nuclear capacity (e.g. 100 and 90%), the static and dynamic vulnerability of nuclear and oil & LNG show the inverse trend: Oil & LNG has a greater contribution in the dynamic vulnerability while nuclear has a greater contribution in the static vulnerability. Under the lower nuclear capacity (e.g. 60 and 50%), oil & LNG becomes the highest among the assessed power sources in both static and dynamic vulnerability, and its significant difference in the ratio of other power sources to oil & LNG could be observed. Compared to the static vulnerability, the dynamic vulnerability shows the higher ratio of other power sources to oil & LNG for nuclear capacity less than 70%. This would be due to the extremely high degree of vulnerability of power sources in the time range of 08:00-16:00, as previously mentioned. In this case, a slight failure of facilities even with a small capacity has a significant impact on the power system, which increases the risk of sudden disruptions of power supply.

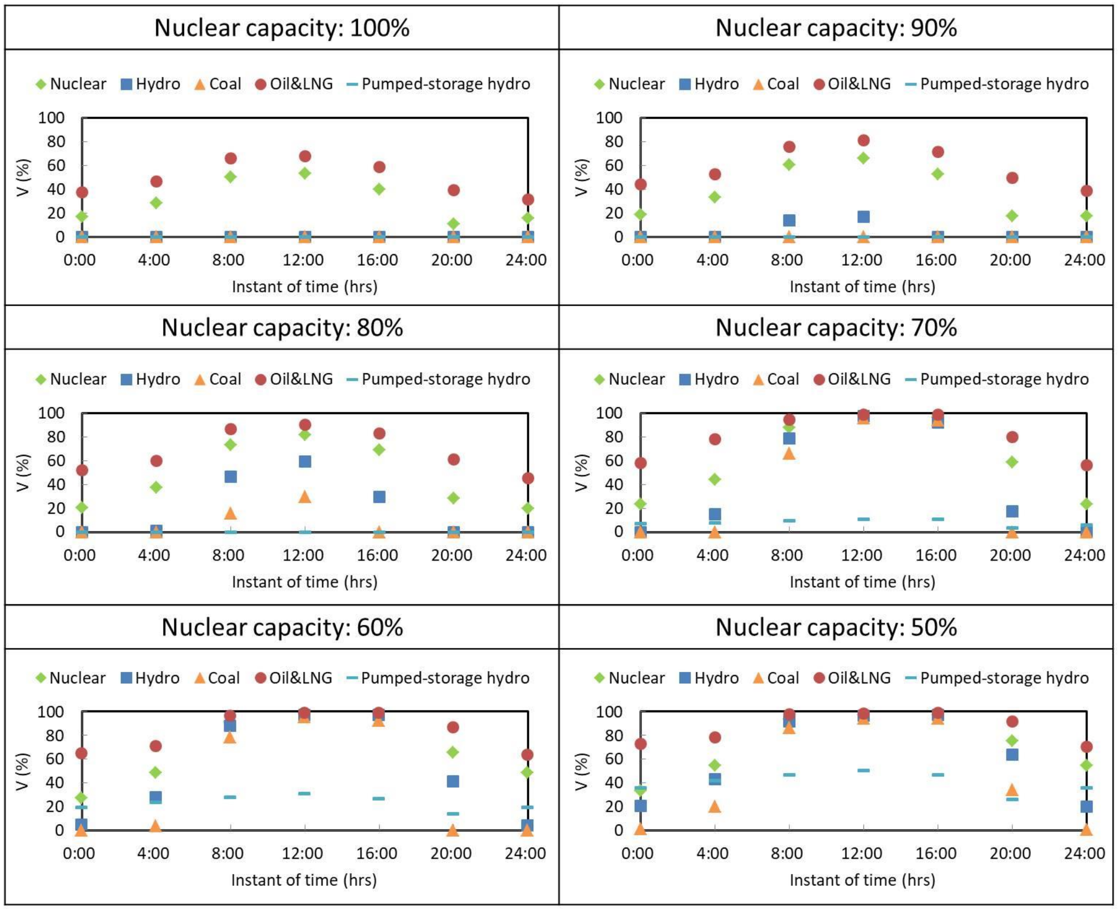

Figure 6.5 Degree of dynamic vulnerability at the assessed instant of time in the centralized network

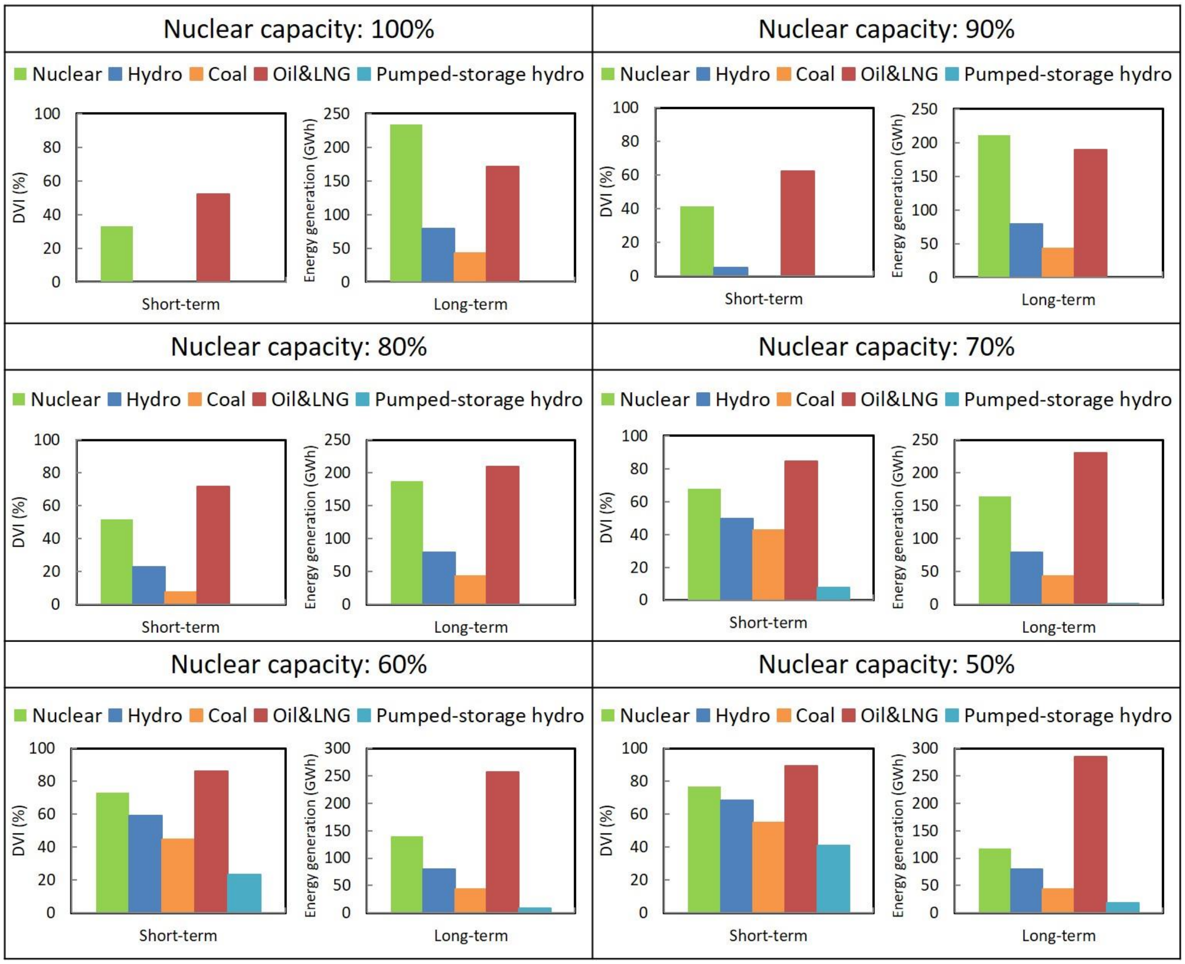

Figure 6.6 Static and dynamic vulnerability of fuels in the centralized network

6.4.2 Distributed network

The degree of dynamic vulnerability at the assessed instant of time in the distributed network (standalone zero energy house in Japan) is presented in Figure 6.7.

The trend in the degree of vulnerability for solar PV strongly depends on its capacity. With solar PV capacity of 15%, the most vulnerable time range for solar PV is from 8:00 to 16:00. Since only the minimum surplus power required for the system is generated under this condition, any disturbance on solar PV hinders the supply of necessary electricity to be stored, thus directly causing a supply disruption. The results for solar PV capacity of 18% and 21% shows somewhat different behavior: the vulnerability reaches its peak at earlier time of the day, e.g. at 04:00. The disturbance on the solar PV supply occurring in early morning requires extension of battery operation time to ensure the continuous supply, and as the residual capacity of the battery is limited after its operation during the nighttime, the disturbance on the solar PV under such condition thus significantly shortens the self-sustainable duration. The degree of vulnerability declines until around 16:00 as the surplus electricity from solar PV is being charged to the battery, which serves as the backup supply and maintains the sustainable electricity supply. After the operation of PV is interrupted, the power supply is totally dependent on battery, and thus the vulnerability of solar PV then starts to increase as the amount of residual capacity, or backup supply capability of the battery decreases.

The difference of degree of vulnerability with time between the maximum and minimum for battery is within approximately 25%, and is significantly smaller than that for solar PV which is within approximately 80%. This is due to the difference in the operational duration characteristics of the two systems; battery operates continuously throughout the day (e.g. charging during daytime and discharging during elsewhere) while solar PV operates only during the day time and does not contribute to the continuous power supply for the rest of the day. The dynamic vulnerability for the battery with time is found to exhibit the same trend regardless of its capacity size. The distributed system is found to be more vulnerable at the battery charging after noon by approximately 40% at most, compared to that at the battery discharging period. This trend is opposite to that for solar PV, particularly in the case of solar capacity of 18% and 21%. As long as the battery could continuously operate until the restart of solar PV operation after the supply disturbance, the system could be self-sustained during the daytime and thus the sustainable duration of stable supply could be consequently extended. In addition, the occurrence of disturbances on battery during daytime leads to reduction of the residual capacity of the battery, and therefore, the degree of vulnerability for battery after midnight until early morning is significantly lower than after noon until evening.

Using the thus obtained degree of dynamic vulnerability at the assessed instant of time for the distributed network, the energy generation and dynamic vulnerability of each electricity source is computed and then their proportion of the static and dynamic vulnerability was obtained. The result is presented in Figure 6.8.

No significant change in the proportion of energy generation for the long-term diversity is observed among the assessed capacity combinations. Solar PV contributes to approximately 70% of the long-term power supply. On the contrary, significant difference in the proportion of dynamic vulnerability for the short-term diversity is observed among the assessed capacity combinations. Under the same capacity of solar PV, the proportion of vulnerability on battery decreases with increasing capacity of battery. This trend is also seen in the case of solar PV; that is, under the same capacity of battery, the proportion of vulnerability on solar PV decreases with increasing capacity of solar PV. This is because the vulnerability of one source to supply disruption is relatively deteriorated due to the increase in capacity of the other power source.

Notably, the trend in the proportion of energy generation for the long-term diversity is significantly different from that of dynamic vulnerability for the short-term diversity. In particular, some capacity combinations show the inverse trend, in which the solar PV has a greater contribution in the context of energy generation (e.g. long term) while the battery has a greater contribution in the context of dynamic vulnerability (e.g. short term). This is because battery operates throughout the day for charging and discharging in the distributed system and the degree of dynamic vulnerability for the battery is higher than that for solar PV other than early in the morning, as previously mentioned. Although the maximum demand load curve in Japan on a sunny day with full operation of the solar PV is adopted in this case study, it should be noted that the power system for the short term surprisingly relies significantly on battery rather than solar PV in terms of short-term dynamic vulnerability. This inverse trend between the static and dynamic vulnerability reveals the significant importance of the use of battery from the short-term perspective. Although it has been reported that the battery plays an important role on the improvement of system security owning to its quick and dynamic response [162, 186, 187], the approach adopted in this study would further aid to quantify the ability of the system to withstand sudden disturbances and to clarify the role of each system component to different timescale of vulnerability in detail, which has not been mentioned in the conventional approach.

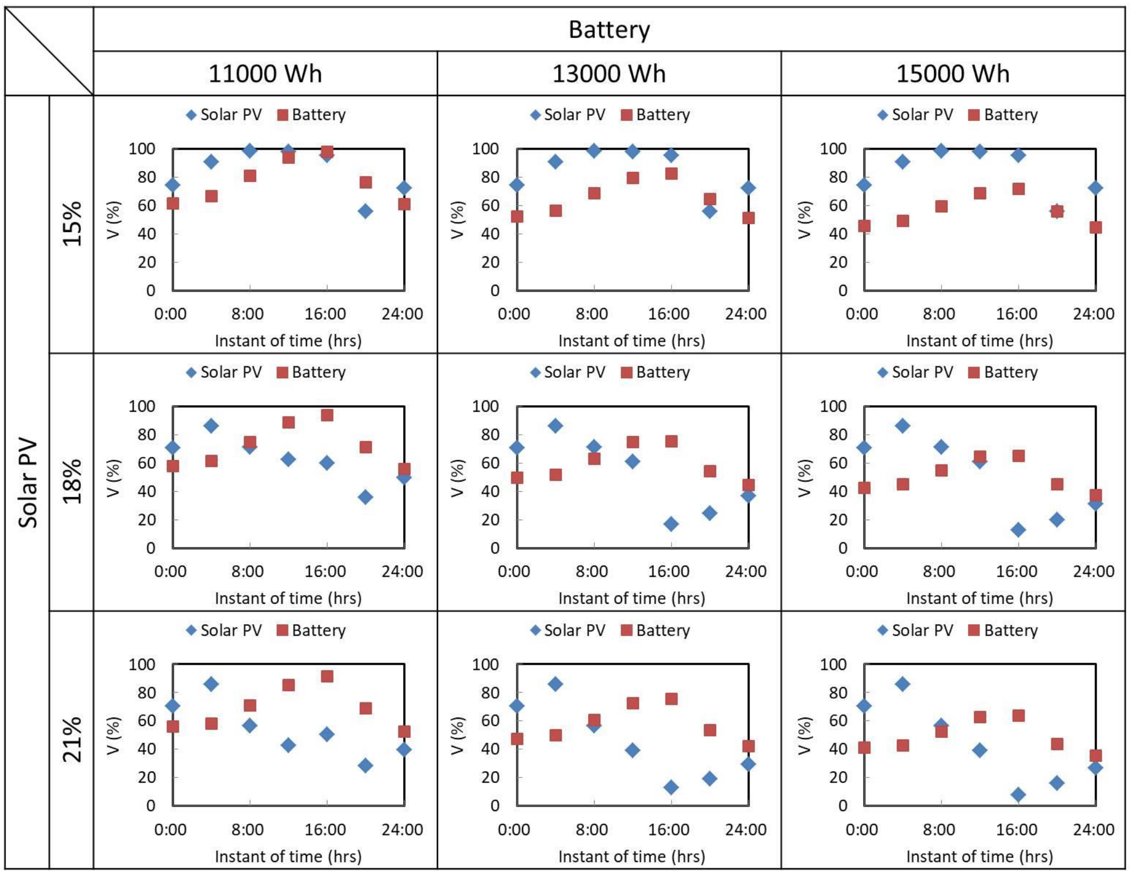

Figure 6.7 Degree of dynamic vulnerability at the assessed instant of time in the distributed network

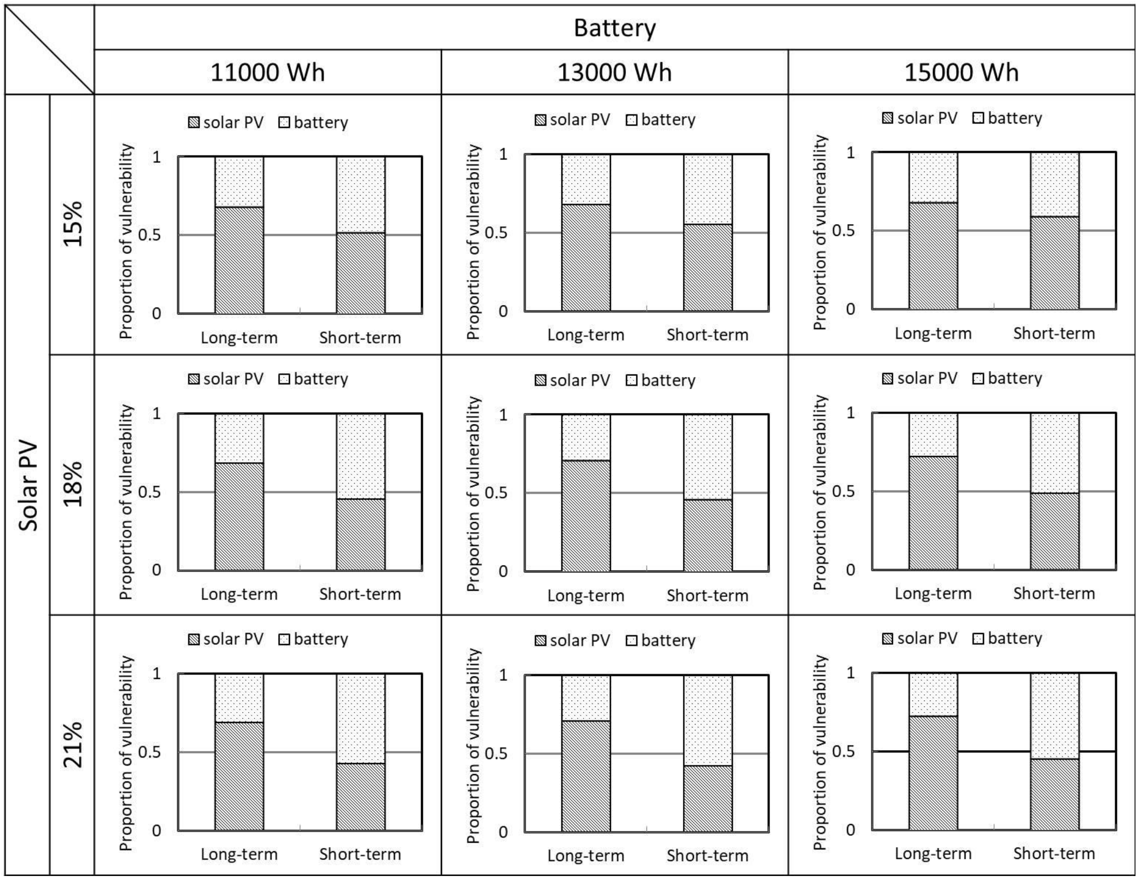

Figure 6.8 Static and dynamic vulnerability of fuels in the distributed network

6.5 Discussion and conclusion

As highlighted in the previous section, the static and dynamic vulnerability by each of power sources in the distributed network and in the centralized network are shown to exhibit totally different trend in both network systems. It should be noted that, since this study is based on simplified model of fictitious power network and the actual values of system behavior after sudden disturbances do not exist, present results based on parametric analysis cannot be directly verified through comparison with the actual data of existing energy system.

The different degree of vulnerability and even the inverse trend by each of power sources between dynamic and static vulnerability that have been found through this study would raise a concern on policy measures in terms of ensuring and assessing diversity in power mix. The conventional long-term notion based only on energy generation and capacity may potentially have a risk of overlooking the hidden factors associated with the dynamic vulnerability. We should recognize that the distributed network in the context of short-term approach may be more diversified compared to that in the context of long-term approach as shown in the various capacity combinations in this study.

There are limited indicators and indices for representing the ability of system to withstand short-term sudden disturbances (e.g., ratio of energy consumption to production and reserve margin), whereas these indicators cannot be used to adequately monitor the role of each power source. In addition, the existing system reliability indices are based upon the past experience of the whole grid system, and can hardly take into account the prediction results of power disruption risk due to sudden disturbances. In this context, the method for evaluating dynamic vulnerability proposed in this study would support in tracking the different behavior of each power source on the basis of model simulation. An attractive point of this method might be that the dynamic vulnerability in any electricity system network could be estimated just by changing the demand and power capacity as input data.

Despite the low contribution of storage technology to power output in the current energy landscape, it is expected that its contribution increases with accelerated installation of distributed network, especially in local and rural regions. Considering the significant role of storage technology in securing dynamic vulnerability highlighted in this study, it is important to further discuss how to address the contribution of storage technology in the assessment of diversity in power mix.

Diversity in power mix has been also described on the basis of shares in generation capacity. It should be noted that the approach of accounting only for the power source-wise generation capacity in the diversity assessment cannot be simply applied to storage technology. As has been described for the centralized network, the storage capacity is also an essential factor for a continuous power supply since the use of storage technology is highly associated with time-series availability.

Such behavior of storage technology complicates the boundary in accounting for energy generation. The power landscape has been demand-oriented so far, in which the power generation is intentionally matched with the demand, and the assessment of diversity has conventionally addressed the generated energy to be used directly to meet the demand. However, the increasing share of renewable energy may require a paradigm shift from the demand-oriented to the supply-oriented power control. The extended use of renewable energy may potentially generate somehow needless surplus power regardless of the demand, and as seen in the case of distributed network, intelligent use of surplus power by installation of adequate and appropriate battery capacity would demonstrate the features of the supply-oriented power control. From this point of view, the whole energy generation including surplus energy used for charging storage devices has to be covered for adequate evaluation of dynamic vulnerability, as has been done in this study. An important argument towards this approach would be that the surplus electricity generated by the power sources is used for battery operation, and in reality the reliance of this surplus energy is thus somehow overlapped with multiple power sources. By reconsidering the boundary and concept of diversity in power mix, whether to count only on the energy used for meeting demand (e.g. excluding excess energy) or to cover the whole energy generation as employed in this study need to be further investigated in more depth.

As for the concept of dynamic vulnerability and diversity, the dynamic vulnerability of a given power source is defined as the degree in which the continuous power supply in the electricity system is disrupted due to a sudden disturbance at the facilities of that power source. This concept matches the conventional concept of long-term diversity based on the reliance on a given power source in energy generation.

On the contrary, diversity could be also interpreted in other words; even if a given power source is disturbed, the continuous power supply is secured as long as other sources can compensate the disruption. In this sense, the subject to be focused is not only the power source being suddenly disturbed but also the role of intact energy sources serving to compensate the disturbance. In the analysis of distributed network, where only two power components, solar PV and battery, are included, we can interpret as the dynamic vulnerability of a power source implicitly indicates the ability of the other component to compensate its disturbance. On the other hand, in the analysis of centralized network, multiple intact power sources are involved in addressing its disruption and thus such interpretation of simple compensation could not be applied. The extension of the model structure is further required to analyze the individual dynamics of each of intact power sources after the occurrence of sudden disturbances on a single energy source in detail.

This Chapter analyzed the difference of diversity in power mix between the long-term perspective conventionally developed and the short-term perspective newly addressed in this thesis (corresponding to the central question).

CHAPTER 7 : CONCLUSION

7.1 Addressing research questions and objective

While aspects of diversity in power mix have been widely studied in detail by a wide range of scholars accounting for energy generation by power source as static vulnerability based on stresses, this study aims to fill the gap in the studies regarding the dynamic vulnerability of an electricity system against the disruption of continuous electricity supply caused by sudden disturbances on an electricity supply under the notion of shocks. The objective of this study was 1) to conceptualize the dynamic vulnerability, 2) to develop the methodology for its quantification, and 3) to analyze the static and dynamic vulnerability of vital electricity system in the context of diversity in power mix. In this Chapter, the main research question and sub-questions are answered.

7.1.1 Sub-Q1: What is the concept of dynamic vulnerability proposed in this study?

Diversity in power mix acts to moderate the vulnerability of an electricity system against the disruption of continuous energy supply caused by an interruption of a single electricity supply source. Considering that the interruption of a power supply course has two natures including stresses under the long-term and static condition and shocks under the short-term and dynamic condition, this study focused on static vulnerability based on stresses and dynamic vulnerability based on shocks. It was clarified that, as the boundary of diversity in power mix, the static vulnerability is relevant to the stage of primary energy resource procurement, whereas the dynamic vulnerability corresponds to the stage of power generation at facilities.

The conventional notion of diversity in power mix has been examined in the context of the static vulnerability of power system to continuous power system by accounting for the share of power generation by each power source. Such vulnerability is fundamentally based upon sufficiency of power generation to meet demand. To analyze the difference of the trend between static and dynamic vulnerability, the concept of sufficiency was also applied to the dynamic vulnerability of the electricity system to the disruption of continuous power supply arising from a sudden disturbance at the facilities on a single energy source. In particular, the ability of the power system to withstand sudden interruption of system components was interpreted as the degree of sufficiency of power generation to meet demand. In other words, the dynamic vulnerability depends on whether the system maintains supply capability to generate sufficient power for meeting demand even after an occurrence of sudden interruption of electricity supply source. The system which maintain the minimum supply capability can remain self-sufficient.

7.1.2 Sub-Q2: How can the dynamic vulnerability be quantified in the context of diversity in power mix?

Based on the developed concept, the methodology for evaluating short-term diversity in the context of diversity in power mix needs to cover the several characteristics including sufficiency, a focus on the generation stage under HL-1, vulnerability potentially contained in the system, a focus on each power source, and consideration of time-series notion. There are limited indices dedicated for short-term energy security such as reliability indices, and each index focuses on a specific feature in short-term energy security, whilst they do not sufficiently cover the concept of dynamic vulnerability assessed in this study. Therefore, the quantified method and index dedicated for the dynamic vulnerability in the context of diversity in power mix was newly required to be finally applied to short-term energy security study.

This study has determined the scale of sudden disturbances based on the magnitude and duration of disturbances on facilities for power generation at an arbitrary time. There would be a threshold of magnitude and duration of disturbances that the power system can maintain the supply capability in a self-sufficient manner. Its threshold indicates that the greater threshold corresponds to the lower dynamic vulnerability of power system to supply disruptions due to sudden disturbances. In other words, the combination of the greatest accepted magnitude of failure and the longest accepted duration of failure at a given instant leads to a power system with the most resilient supply capability at an arbitrary time. Algorithm of identifying its threshold has been developed in this thesis to quantify the degree of power system to maintain supply-capability, or the degree of vulnerability of power system to disruption of power supply, vice versa.

7.1.3 Sub-Q3: What index dedicated for the dynamic vulnerability should be developed?

By using the obtained greatest accepted magnitude of failure and the longest accepted duration of failure at a given instant based on the developed methodology, the three types of curves (DI curve, RI curve and DR curve) has been depicted. Then, the area under the depicted curve has been computed to develop an index dedicated for the dynamic vulnerability, or for the system security.

This index has been introduced in multiple manners depending on which power source is focused in the analysis of sudden disturbances, for instances: the SINVI for nuclear power in centralized network (Chapter 4), the solar PV security and battery security for renewables and storage technology in distributed network (Chapter 5), and DVI for any type of power source in both centralized and distributed network (Chapter 6).

7.1.4 Sub-Q4: How can the developed index dedicated for dynamic vulnerability be applied?

Diversity in power mix has contributed to design of the electricity system and determination of the capacity sizing. In the dimensioned-based approach for the analysis of national energy security, energy generation by power source as static vulnerability in a national scale of electricity system was accounted for to be applied into determination of capacity size. Additionally, in the process of determining capacity size in the distributed system, system adequacy alone has been utilized in the reliability assessment. Since dynamic vulnerability is simply dimmed out from their assessments for determining capacity size, the applicability of developed index dedicated for dynamic vulnerability into a given electricity system needs to be demonstrated for the comparison of static and dynamic vulnerability and for the contribution to determining capacity size.

The core of dynamic vulnerability in this study is based upon the self-sufficiency of power system without any reliance on externalities even after sudden disturbances on facilities of power source. Due to this essential, this study assessed the standalone power system disconnected with any other external power network. By applying the developed index dedicated for the dynamic vulnerability into the standalone centralized network and distribution network, this study demonstrated its applicability through the comparison of static and dynamic vulnerability for the well-understanding of diversity in power mix and through cost-effectiveness analysis for determining capacity size with a consideration of sudden disturbances.

7.1.5 Central question: What is the difference of trend between static and dynamic vulnerability in the context of diversity in power mix in energy security?

The static and dynamic vulnerability in the context of diversity in power mix has been discussed in this thesis. Based on the conceptualization of dynamic vulnerability, the methodology for assessing the dynamic vulnerability of the electricity system to the disruption of continuous power supply due to sudden disturbances has been developed. By using the developed method, static and dynamic vulnerability characteristics have been obtained and compared for fictitious electricity demand and supply system.

In the fictitious distributed network within a one-day snapshot, the trend of static vulnerability is significantly different from that of dynamic vulnerability. In particular, some specific capacity combinations exhibited an inverse trend between static and dynamic vulnerability, in which the solar PV has the greater contribution in the context of static vulnerability while the battery has the greater contribution in the context of dynamic vulnerability.

In the fictitious centralized network within a one-day snapshot, the comparison of static and dynamic vulnerability exhibits notably different trend. Under the greater input capacity, the static and dynamic vulnerability of nuclear and oil & LNG show the inverse trend. Under lower input capacity, oil & LNG is highest among the assessed power sources in both static and dynamic vulnerability, but its significant difference in the ratio of other power sources to oil & LNG was observed.

The different degree of vulnerability and even the inverse trend by each of power sources between static and dynamic vulnerability has been highlighted in certain fictitious distributed and centralized network within in a one-day snapshot. As such, the objective of this study which aims to 1) to conceptualize the dynamic vulnerability, 2) to develop the methodology for its quantification, and 3) to analyze the static and dynamic vulnerability of vital electricity system in the context of diversity in power mix had been achieved and all the problem statements had been addressed in this study.

7.2 Contribution of research

a) Highlighting a new concern on nuclear power use

A new concern on nuclear power use in terms of energy security has been highlighted in this thesis. Nuclear-related issues including public opinion, safety, and nuclear non-proliferation have been considered so far in the energy security narratives. In addition, most of research works have qualitatively addressed this matter and its consequence has yet to be fully quantitatively analyzed. Meanwhile, for the first time, this study has analyzed the sudden supply disruption particularly associated with nuclear energy utilization due to the different societal issue such as governmental decision and lawsuits considered as a new and significant risk to domestic energy supply security.

b) Quantitative presentation of significant role of storage technology in securing power supply

In spite of drawbacks of storage technology (e.g. the capital and maintenance costs and unavoidable energy losses through the round-conversion process), the contribution of storage technology to the continuous electricity supply has been qualitatively and theoretically highlighted so far. Meanwhile, its ability to withstand sudden disturbances on power system has yet to be fully evaluated in a quantitative manner. By using the methodology developed in this thesis, it has even potentially implied the greater contribution of the battery to continuous power supply compared with the solar PV in the distributed system. Despite the low contribution of storage technology to power output in the current energy landscape, it is expected that its contribution increases with accelerated installation of distributed network, especially in local and rural regions. This finding would assist in removing barriers in installation of battery equipment to some extent.

c) Establishment of a new index dedicated for short-term energy security

The prediction of continuous electricity supply security after sudden disturbances on power sources will help the utility manager to make an appropriate action based on the information on the DI, RI, DR curves obtained by using the developed methodology in this thesis.

There are limited indicators and indices for representing the short-term energy security (e.g., ratio of energy consumption to production and reserve margin), and each of them focuses on a specific feature in short-term energy security. For example, these existing indicators cannot be used to adequately monitor the role of each power source, and some of them are based upon the past experience of the whole grid system, and can hardly take into account the prediction results of power disruption risk due to sudden disturbances. In this context, the developed methodology and index for evaluating dynamic vulnerability in the context of diversity in power mix could cover the several characteristics including sufficiency, a focus on the generation stage under HL-1, vulnerability potentially contained in the system, a focus on each power source, and consideration of time-series notion.

d) Direct adoption of developed methodology and index to any other power system networks

Although this study employed the case of both centralized and distributed network in Japan, the dynamic vulnerability in any electricity system network could be estimated just by changing the demand and power capacity as input data. This is an attractive point of this method.

e) New insights on diversity in power mix

Through this study, we have identified the necessity to reconsider the design policy of the electricity supply system in terms of evaluating diversity in power mix from the perspective of not only static vulnerability but also dynamic vulnerability. Relying only on energy generation and capacity, which is the conventional approach for long-term diversity evaluation, may potentially bear significant risk overlooking the hidden factors associated with the dynamic vulnerability. The major results and findings of this study shall add a new view to energy security assessment and sustainable energy resource supply strategy, which is becoming more important in energy policy design.

7.3 Future work

As a starting point of quantitatively analyzing energy security based on vulnerability-based approach, this study focused on the vulnerability of power system in the context of diversity in power mix. A new insight on diversity in power mix was presented through this analysis by using such approach, whilst consideration of the following aspects would assist in in-depth understanding of diversity in power mix, vulnerability-based approach and practical implications in energy security study.

a) Interpretation of diversity in power mix

In this study, diversity in power mix was based on the vulnerability of power mix caused by the interruption of each power source. On the contrary, diversity could be also interpreted in other words; even if a given power source is disturbed, the continuous power supply is secured as long as other sources can compensate the disruption. In this sense, the subject to be focused is not only the power source being suddenly disturbed but also the role of intact energy sources serving to compensate the disturbance. In the analysis of distributed network, where only two power components, solar PV and battery, are included, we can interpret as the dynamic vulnerability dedicated for a power source implicitly indicates the ability of the other component to compensate its disturbance. On the other hand, in the analysis of centralized network, multiple intact power sources are involved in addressing its disruption and thus such interpretation of simple compensation could not be applied. The extension of the model structure is further required to analyze the individual dynamics of each of intact power sources after the occurrence of sudden disturbances on a single energy source in detail.

b) Vulnerability-based approach

Under the vulnerability-based approach in energy security study, this study focused on diversity as one of the features in resilience and shocks and stresses as features in risk. Meanwhile, the overall vulnerability potentially contained in vital energy systems contains various features in both risk and resilience. For instances, several concepts are involved even in the concept of risk, including the term “hazard” and “threat”. Although Cherp and Jewell pointed out flexibility and diversity as the components of resilience, there are other various features presented in the resilience narrative such as “adaptability”, “redundancy”, and “interdependency”. In particular, the role of intact energy sources serving to compensate the disturbance previously mentioned as the different interpretation of diversity in power mix would be somewhat relevant to the concept of “flexibility” and “adaptability”. Further analysis of different features of both risk and resilience would aid in well-understanding of energy security based on the vulnerability-based approach.

c) Practical applications

Although the developed algorithm was employed in the theoretically-based system in this study, its practical application to the real world and inclusion of factors such as technical constraints and innovative technologies would be required. In practice, sudden disturbances in power generation facilities complicate the retention of stability in rotor angle, voltage and frequency [96]. In addition, it is highly expected in future that the energy consumption would be optimized through a use of demand response tool under the concept of energy saving. The interest in analyzing the impact of demand response tool on the hybrid renewable energy system in the static condition has increasingly grown as a research topic (e.g., [188, 189, 190]). Given that the balance between demand and supply is monitored through the two way communication technology, the demand side can be managed even under the emergency [191]. The inclusion of these practical features in the developed algorithm might also assist in determining the optimal capacity size in the real centralized grid system with distributed system from the perspective of energy security.

REFERENCES

[1] B. W. Ang, W. L. Choong and T. S. Ng, "Energy security: Definitions, dimensions and indexes," Renewable and Sustainable Energy Reviews 42, pp.1077-1093, 2015.

[2] IEA, "Energy security," IEA, 2020.

[3] United Nations, "Energy security," United Nations, 2000.

[4] IEEJ, "Energy security and challenges for Japan," IEEJ, 2012.

[5] C. Winzer, "Conceptualizing energy security," Energy Policy, 46, pp.36-48, 2012.

[6] A. Loschel, U. Moslener and D. Rubbelke, "Indicators of energy security in industrialised countries," Energy Policy 38, 4, pp.1665-1671, 2010.

[7] A. Checchi, A. Behrens and C. Egenhofer, "Long-term energy security risks for europe, a sector-sepecific approach," CEPS working document, 309, 2009.

[8] J. Jewell, A. Cherp and K. Riahi, "Energy security under de-carbonization scenarios: An assessment framework and evaluation under different technology and policy choices," Energy Policy 65, pp.743-760, 2014.

[9] V. Vivoda, "Evaluating energy security in the Asia-Pacific refion: A novel methodological approach," Energy Policy, 38, pp.5258-5263, 2010.

[10] B. K. Sovacool, "Evaluating energy security in the Asia pacific: Towards a more comprehensive approach," Energy Policy, 39, pp.7472-7479, 2011.

[11] A. Cherp, "Defining energy security takes more than asking around," Energy Policy, 48, pp.841-842, 2012.

[12] A. Cherp and J. Jewell, "The three perspectives on energy security: intellectual history, disciplinary roots and the potential for integration," Current Opinion in Environmental Sustainability 3, pp.202-212, 2011.

[13] J. P. Rutherford, E. W. Scharpf and C. G. Carrington, "Linking consumer energy efficiency with security of supply.," Energy Policy 35 (5), 3025–3035, 2007.

[14] A. E. Farrell, H. Zerriffi and H. Dowlatabadi, "Energy Infrastructure and security," Annu. Rev. Environ. Resour., 24, pp.421-469, 2004.

[15] A. Cherp and J. Jewell, "The concept of energy security: Beyond the four As," Energy Policy, 75, pp.415-421, 2014.

[16] A. Wolfers, "'National Security' as an ambiguous symbol," Polit. Sci. Q., 67 (4), pp. 481-502, 1952.

[17] M. Grubb, L. Butler and P. Twomey, "Diversity and security in UK electricity generation: the influence of low-carbon objectives," Energy Policy, 34, pp.4050–4062, 2006.

[18] M. A. Paim, A. R. Dalmarco, C. H. Yang, P. Salas, S. Lindner, J. F. Mercure, J. B. S. O. D. Guerra, C. Derani, T. B. da Silva and J. E. Vinuales, "Evaluating regulatory strategies for mitigating hydrological risk in Brazil through diversification of its electricity mix," Energy Policy, 128, pp.393-401, 2019.

[19] N. Victor, C. Nichols and P. Balash, "The impacts of shale gas supply and climate policies on energy security: The U.S. energy system analysis based on MARKAL model," Energy Strategy Review, 5, pp.26-41, 2014.

[20] V. Vivoda, "Diversification of oil import sources and energy security: a key strategy or an elusive objective?," Energy Policy, 37, pp.4615-4623, 2009.

[21] A. Ranjan and L. Hughes, "Energy security and the diversity of energy flows in an energy system," Energy, 73, pp.137-144, 2014.

[22] D. Yergin, "Ensuring energy security," Foreign affairs, 85, pp.69-82, 2006.

[23] A. Stirling, "Multicriteria diversity analysis: a novel heuristic framework for appraising energy portfolios," Energy Policy 38 (4), pp.1622–1634, 2010.

[24] A. Stirling, "On the Economics and Analysis of Diversity," Report no. Working Paper 28. SPRU, Brighton, 1998.

[25] B. K. Sovacool and I. Mukherjee, "Conceptualizing and measuring energy security: A synthesized approach," Energy, 36 (8), pp.5343-5355, 2011.

[26] C. Folke, S. Carpenter, B. Walker, M. Scheffer, T. Elmqvist, L. Gunderson and C. S. Holling, "Regime shifts, resilience, and biodiversity in ecosystem management, Annual Review of Ecology," Evolution and Systematics, 35, pp.557-581, 2004.

[27] H. Cooke, I. Keppo and S. Wolf, "Diversity in theory and practice: A review with application to the evolution of renewable energy generation in the UK," Energy Policy, 61, pp.88-95, 2013.

[28] IEA, "IEA Sankey diagram," IEA, 2018.

[29] E. Kisel, A. Hamburg, M. Harm, A. Leppiman and M. Ots, "Concept for Energy Security

Matrix," Energy Policy, 95, pp.1-9, 2016.

[30] World Energy Council, "2013 Energy Sustainability Index," available at https://www.worldenergy.org/wp-content/uploads/2013/09/2013-Energy-Sustainability-Index-VOL-2.pdf (accessed 30.4.2019), 2013.

[31] World Economic Forum, "The Global Energy Architecture Performance Index Report 2014," available at http://www3.weforum.org/docs/WEF_EN_NEA_Report_2014.pdf (accessed 30.4.2019), 2013.

[32] Asia Pacific Energy Research Centre (APERC), "A Quest for Energy Security in the 21st century," Institute of energy econmics, Japan, 2007.

[33] W. Blyth and N. Lèfefre, "Energy security and climate change: an assesement framework," OECD/International Energy Agency Information Ppaer. Paris, France, 2004.

[34] D. Gotham, K. Muthuraman, P. Preckel, R. Rardin and S. Ruangpattana, "A load factor based mean–variance analysis for fuel diversification," Energy Economics, 31, pp.249-256, 2009.

[35] F. de-Llano Paz, S. I. Antelo, A. Calvo Silvosa and I. Soares, "The technological and environmental efficiency of the EU-27 power mix: An evaluation based on MPT," Energy, 69, pp.67-81, 2014.

[36] A. Stirling, "From sustainability, through diversity to transformation: towards more reflexive governance of technological vulnerability," In: Hommels, A, Mesman, J and Bijker, W (eds.) Vulnerability in technological cultures: new directions in research and governance. Inside technology. MIT Press, Cambridge, MA, 2014.

[37] F. Gracceva and P. Zeniewski, "A systemic approach to assessing energy security in a low-carbon EU energy system," Applied Energy, 123, pp.335-348, 2013.

[38] J. C. Jansen and A. J. Seebregts, "Long-term energy services security: what is it and how can it be measured and valued?," Energy Policy, 38 (4), pp. 1654-1664, 2010.

[39] M. C. Chuang and H. W. Ma, "Energy security and improvements in the function of diversity indices-Taiwan energy supply structure case study," Renewable & Sustainable Energy Reviews, 24, pp.9-20, 2013.

[40] J. N. V. Lucas, G. E. Frances and E. S. Gonzalez, "Energy security and renewable energy deployment in the EU: Liaisons Dangereuses or Virtuous Circle?," Renewable & Sustainable Energy Reviews, 62, pp.1032-1046, 2016.

[41] S. Zhang, T. Zhao and B. C. Xie, "What is the optimal power generation mix of China? An empirical analysis using portfolio theory," Applied Energy, 229, pp.522-536, 2018.

[42] B. Brand and R. Missaoui, "Multi-criteria analysis of electricity generation mix scenarios in

Tunisia," Renewable & Sustainable Energy Reviews, 39, pp.251-261, 2014.

[43] M. A. H. Mondal, C. Ringler, P. Al-Riffai, H. Eldidi, C. Breisinger and M. Wiebelt, "Long-term optimization of Egypt's power sector: Policy implications," Energy, 166, pp.1063-1073, 2019.

[44] P. Nahmmacher, E. Schmid, M. Pahle and B. Knopf, "Strategies against shocks in power systems - An analysis for the case of Europe," Energy Economics, 59, pp.455-465, 2016.

[45] C. Batlle, C. Vazquez, M. Rivier and I. J. Perez-Arriaga, "Enhancing power supply adequacy in Spain: migrating from capacity payments to reliability options," Energy Policy, 35 (9), pp.4545-4554, 2007.

[46] B. Kruyt, D. P. van Vuuren, H. J. M. de Vries and H. Groenenberg, "Indicators for energy security," Energy Policy, 37 (6), pp.2166-2181, 2009.

[47] K. Costrllo, "Diversity of generation technologies: implications for decision-making and public policy," The Electricity Journal, 20 (5), pp.10-21, 2007.

[48] J. C. Jansen, W. G. van Arkel and M. G. Boots, "Designing indicators of long term security," ECN-C—04–007. Energy Research Centre of the Netherlands. Petten, 2004.

[49] M. Benidris, J. Mitra and C. Singh, "Integrated Evaluation of Reliability and Stability of Power Systems," IEEE Transactions on Power Systems, 32 (5), pp.4131-4139, 2017.

[50] A. M. Rei, A. M. Leite da Silva, J. L. Jardim and J. C. O. Mello, "Static and dynamic aspects in bulk power system reliability evaluations," IEEE Transactions on Power Systems, 15 (1), pp.189-195, 2000.

[51] A. Y. Takahata, M. G. dos Santos, G. N. Taranto and M. T. Schilling, "Computational framework combining static and transient power system security evaluation using uncertainties," International Journal of Electrical Power & Energy Systems, 71, pp.151-159, 2015.

[52] H. Hu and G. Augenbroe, "A stochastic model based energy management system for off-grid solar houses," Building and Environment, 50, pp.90-103, 2012.

[53] J. Stern, "Security of European Natural Gas Supplies," available at http://www.bgc.bg/upload_files/file/Security_of_Euro_Gas_.pdf (accessed 29.5.2019), 2002.

[54] A. Creti and N. Fabra, "Supply security and short-run capacity markets for electricity," Energy Economics, 29(2), pp.259–276, 2007.

[55] F. Smith, "Biological diversity, ecosystem stability and economic development," Ecological Economics, 16, pp.191-203, 1996.

[56] J. B. Kucharski, "Energy security in Japan in the context of a planned energy system transition," A dissertation in the Graduate School of Energy Science of Kyoto University, 2016.

[57] A. Castillo, "Risk analysis and management in power outage and restoration: A literature review," Electric Power System Research, 107, pp.9-15, 2014.

[58] R. Allan, "Power system reliability assessment-a conceptual and historical review," Reliability Engineering & System Safety, 46 (1), pp.3-13, 1994.

[59] R. Allan and R. Billinton, "Probabilistic assessment of power systems," Proceedings of the IEEE, 88 (2) pp.140–162, 2000.

[60] S. Diaf, D. Diaf, M. Belhamel, M. Haddadi and A. Louche, "A methodology or optimal sizing of autonomous hybrid PV/wind system," Energy Policy, 35 (11), pp.5708-5718, 2007.

[61] S. Diaf, M. Belhamel, M. Haddadi and A. Louche, "Technical and economic assessment of hybrid photovoltaic/wind system with battery storage in Corsica island," Energy Policy, 36 (2), pp.743-754, 2008.

[62] S. Diaf, G. Notton, M. Belhamel, M. Haddadi and A. Louche, "Design and techno-economical optimization for hybrid PV/wind system under various meteorological conditions," Applied Energy, 85 (10), pp.968-987, 2008.

[63] H. X. Yang, L. Lu and W. Zhou, "A novel optimization sizing model for hybrid solar-wind power generation system," Solar Energy, 81 (1), pp.76-84, 2007.

[64] S. Semaoui, A. H. Arab, S. Bacha and B. Azoui, "Optimal sizing of a stand-alone photovoltaic system with energy management in isolated areas," Energy Procedia, 36 pp.358-368, 2013.

[65] J. H. Cho, M. G. Chun and W. P. Hong, "Structure Optimization of Stand-Alone Renewable Power Systems Based on Multi Object Function," Energies, 9 (8), 649, 2016.

[66] S. Das and A. K. Akella, "Power Flow Control of PV-Wind-Battery Hybrid Renewable Energy Systems for Stand-Alone Application," International Journal of Renewable Energy Research, 8 (1), pp.36-43, 2018.

[67] P. P. Vergara, J. M. Rey, L. C. P. da Silva and G. Ordóñez, "Comparative analysis of design criteria for hybrid photovoltaic/wind/battery systems," IET Renewable Power Generation, 11 (3), pp.253-261, 2017.

[68] W. X. Peng, A. Maleki, M. A. Rosen and P. Azarikhah, "Optimization of a hybrid system for solar-wind-based water desalination by reverse osmosis: Comparison of approaches," Desalination, 442, pp.16-31, 2018.

[69] M. A. M. Ramli, H. R. E. H. Bouchekara and A. S. Alghamdi, "Optimal sizing of

PV/wind/diesel hybrid microgrid system using multi-objective self-adaptive differential evolution algorithm," Renewable Energy, 121, pp.400-411, 2018.

[70] P. Arun, R. Banerjee and S. Bandyopadhyay, "Optimum sizing of photovoltaic battery systems incorporating uncertainty through design space approach," Solar Energy, 83 (7), pp.1013-1025, 2009.

[71] S. Zolfaghari, G. H. Riahy, M. Abedi and S. Golshannavaz, "Optimal wind energy penetration in power systems: An approach based on spatial distribution of wind speed," Energy Conversion and Management, 118, pp.387-398, 2016.

[72] A. Roy, S. B. Kedare and S. Bandyopadhyay, "Optimum sizing of wind-battery systems incorporating resource uncertainty," Applied Energy, 87 (8), pp.2712-2727, 2010.

[73] C. Novoa and T. D. Jin, "Reliability centered planning for distributed generation considering wind power volatility," Electric Power Systems Research, 81 (8), pp.1654-1661, 2011.

[74] A. Q. Jakhrani, A. K. Othman, A. R. H. Rigit, S. R. Samo and S. A. Kamboh, "A novel analytical model for optimal sizing of standalone photovoltaic systems," Energy, 46 (1), pp.675-682, 2012.

[75] H. C. Chen, "Optimum capacity determination of stand-alone hybrid generation system considering cost and reliability," Applied Energy, 103, pp.155-164, 2013.

[76] N. Agarwal, A. Kumar and Varun, "Optimization of grid independent hybrid PV-diesel-battery system for power generation in remote-villages of Uttar Pradesh, India," Energy for Sustainable Development, 17 (3), pp.210-219, 2013.

[77] G. Ma, G. C. Xu, Y. X. Chen and R. Ju, "Multi-objective optimal configuration method for a standalone wind-solar-battery hybrid power system," IET Renewable Power Generation, 11 (1), pp.194-202, 2017.

[78] D. H. Muhsen, T. Khatib and T. E. Abdulabbas, "Sizing of a standalone photovoltaic water pumping system using hybrid multi-criteria decision making methods," Solar Energy, 159, pp.1003-1015, 2018.

[79] S. Rajanna and R. P. Saini, "Modeling of integrated renewable energy system for electrification of a remote area in India," Renewable Energy, 90, pp.175-187, 2016.

[80] A. Kaabeche, M. Belhamel and R. Ibtiouen, "Sizing optimization of grid-independent hybrid photovoltaic/wind power generation system," Energy, 36 (2), pp.1214-1222, 2011.

[81] P. Paliwal, N. P. Patidar and R. K. Nema, "Determination of reliability constrained optimal resource mix for an autonomous hybrid power system using Particle Swarm Optimization," Renewable Energy, 63, pp.194-204, 2014.

[82] L. G. Acuna, R. V. Padilla and A. S. Mercado, "Measuring reliability of hybrid photovoltaic-wind energy systems: A new indicator," Renewable Energy, 106, pp.68-77, 2017.

[83] B. O. Bilal, V. Sambou, P. Ndiaye, C. Kb and M. Ndongo, "Optimal design of a hybrid solar-wind-battery system using the minimization of the annualized cost of the system and the minimization of the loss of power supply probability (LPSP)," Renewable Energy, 35, pp.2388-2390, 2010.

[84] R. Belfkira, L. Zhang and G. Barakat, "Optimal sizing study of hybrid wind/pv/diesel power generation," Solar Energy, 85, pp.100-110, 2011.

[85] R. Dufo-Lpez, J. L. Bernal-Agustin and F. Mendoza, "Design and economical analysis of hybrid pv wind systems connected to the grid for the intermittent production of hydrogen," Energy Policy, 37, pp. 3082-3095, 2009.

[86] G. Merei, C. Berger and D. U. Sauer, "Optimization of an off-grid hybrid pv-wind-diesel system with different battery technologies using genetic algorithm," Solar Energy, 97, pp.460-473, 2013.

[87] B. O. Bilal, V. Sambou, P. A. Ndiaye, C. Kb and M. Ndongo, "Study of the influence of load profile variation on the optimal sizing of a stand-alone hybrid pv/wind/battery/diesel system," Energy Procedia, 36, pp.1265-1275, 2013.

[88] M. Bortolini, M. Gamberi, A. Graziani and F. Pilati, "Economic and environmental bi-objective design of an off-grid photovoltaic-battery-diesel generator hybrid energy system," Energy Conversion and Management, 106, pp.1024-1038, 2015.

[89] S. Ashok, "Optimized model for community-based hybrid energy system," Renewable Energy, 32, pp.1155-1164, 2007.

[90] C. Rubio-Maya, J. Uche-Marcuello, A. Martínez-Gracia and A. A. Bayod-Rújula, "Design optimization of a polygeneration plant fuelled by natural gas and renewable energy sources," Applied Energy, 88 (2), pp. 449-457, 2011.

[91] H. Borhanazad, S. Mekhilef, V. G. Ganapathy, M. Modiri-Delshad and A. Mirtaheri, "Optimization of micro-grid system using MOPSO," Renewable Energy, 71, pp.295-306, 2014.

[92] R. Dufo-López, J. L. Bernal-Agustín and D. M. Rivas-Ascaso, "Design of isolated hybrid systems minimizing costs and pollutant emissions," Renewable Energy, 31, pp. 2227-2244, 2006.

[93] T. Tezer, R. Yaman and G. Yaman, "Evaluation of approaches used for optimization of stand-alone hybrid renewable energy systems," Renewable & Sustainable Energy Reviews, 73, pp.840-853, 2017.

[94] R. Siddaiah and R. P. Saini, "A review on planning, configurations, modeling and optimization techniques of hybrid renewable energy systems for off grid applications," Renewable & Sustainable Energy Reviews, 58, pp.376-396, 2016.

[95] B. Bhandari, K. T. Lee, G. Y. Lee, Y. M. Chou and S. H. Ahn, "Optimization of Hybrid Renewable Energy Power Systems: A Review," International Journal of Precision Engineering and Manufacturing-Green Technology, 2 (1), pp.99-112, 2015.

[96] P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares, N. Hatziargyriou, D. Hill, A. Stankovic, C. Taylor, T. Van Cursem and V. Vittal, "Definition and classification of power system stability," IEEE Transactions on Power Systems, 19 (3) pp.1387-1401, 2004.

[97] North American Electric Reliability Council (NERC), "Glossary of Terms Used in NERC Reliability Standards," web site: www.nerc.com/files/glossary_of_terms.pdf (accessed 1.3.2017), 2017.

[98] W. Li and J. Zhou, "Probabilistic reliability assessment of power system operations," Electric Power Components and Systems, 36 (10), pp.1102-1114, 2008.

[99] A. Almutairi, M. H. Ahmed and M. M. A. Salama, "Probabilistic generating capacity adequacy evaluation: Research roadmap," Electric Power Systems Research, 129, pp.83-93, 2015.

[100] A. A. Kadhem, N. I. A. Wahab, I. Aris, J. Jasni and A. N. Abdalla, "Computational techniques for assessing the reliability and sustainability of electrical power system: A review," Renewable and Sustainable Energy Reviews, 80, pp.175-1186, 2017.

[101] D. S. J. D. Kirschen, "Comparison of risk-based and deterministic security assessments," IET Generation, Transmission, Distribution, 1 (4), pp.527-533, 2007.

[102] E. Ciapessoni, D. Cirio, G. Kjolle, S. Massucco, A. Pitto and M. Sforna, "Probabilistic Risk-Based Security Assessment of Power Systems Considering Incumbent Threats and Uncertainties," IEEE Transactions on Smart Grid, 7 (6), pp.2890-2903, 2016.

[103] J. Yan, Y. F. Tang, H. B. He and Y. Sun, "Cascading Failure Analysis With DC Power Flow Model and Transient Stability Analysis," IEEE Transactions on Power Systems, 30 (1), pp.285-297, 2015.

[104] F. Cadini, G. L. Agliardi and E. Zio, "A modeling and simulation framework for the reliability/availability assessment of a power transmission grid subject to cascading failures under extreme weather conditions," Applied Energy, 185, pp. 267-279, 2017.

[105] A. Moradkhani, M. R. Haghifam and M. Mohammadzadeh, "Failure rate estimation of overhead electric distribution lines considering data deficiency and population variability," International Transactions on Electrical Energy Systems, 25 (8), pp.1452-1465, 2015.

[106] European Comission, "Security of electricity supply," European Comission, 2018.

[107] P. Toft, A. Duero and A. Bieliauskas, "Terrorist targeting and energy security," Energy Policy, 38 (8), pp.4411-4421, 2010.

[108] P. Mitra, V. Vittal, B. Keel and J. Mistry, "A Systematic Approach to n -1-1 Analysis for Power System Security Assessment," IEEE Power and Energy Technology Systems Journal, 3 (2), pp.71-80, 2016.

[109] Nuclear Emergency Response Headquarters, "report of the Japanese government to the IAEA ministrial conference on nuclear safety," http://fukushima.grs.de/sites/default/files/NISA-IAEA-Fukushima_2011-06-08.pdf, Tokyo, 2011.

[110] TEPCO, "Tokyo electronic company press release," http://www.tepco.co.jp//cc/press/index1103-j.html (accessed 15/8/2015), 2011.

[111] D. Jahn and S. Stephan, "German Exceptionalism: The End of Nuclear Energy in Germany!," Environmental Politics, 21 (1), pp.159-164, 2012.

[112] C. F. Young and D. J. Persell, "Biological, chemical, and nuclear terrorism readiness: Major concerns and preparedness of future nurses," Disaster Management & Response, 2 (4), pp.109-114, 2004.

[113] R. Zimmerman, C. Restrepo, N. Dooskin, R. Hartwell, J. Miller, J. S. W. Remington, L. Lave and R. Schuler, "Electricity Case: Main Report – Risk, Consequences, and Economic Accounting," CREATE Report, FEMA Grant EMW-2004-GR-0112, 2005.

[114] Japan Electric Power Exchange, "HJKS," Japan Electric Power Exchange, 2020.

[115] S. Kosai and H. Unesaki, "Conceptualizing maritime security for energy transportation security," Journal of Transportation Security, 9 (3-4), pp.175-190, 2016.

[116] Ministry of Economy, Trade and Industry, "Oil Stockpile," available at: http://www.meti.go.jp/committee/sougouenergy/shigen_nenryo/pdf/015_03_00.pdf (30.7.2017) (in Japanese), 2016.

[117] CIGRE TF 38.03.12 Report, "Power system security assessment: A position paper," ELECTRA, no. 175, 1997.

[118] P. Paliwal, N. A. Patidar and R. K. Nema, "Planning of grid integrated distributed generators: A review of technology, objectives and techniques," Renewable & Sustainable Energy Reviews, 40, pp.557-570, 2014.

[119] T. Ackermann, G. Andersson and L. Soder, "Distributed generation: a definition," Electric Power Systems Research, 57 (3), pp.195-204, 2001.

[120] C. L. T. Borges and D. M. Falcão, "Optimal distributed generation allocation for reliability, losses and voltage improvement," International Journal of Electrical Power & Energy Systems, 28, pp.413-420, 2006.

[121] IEA, "Distributed generation in liberalised electricity markets," OECD Publishing, 2002.

[122] CIGRE, "Impact of increasing contribution of dispersed generation on the Power System," CIGRE SC #37, 1998.

[123] P. Dondi, D. Bayoumi, C. Haederli, D. Julian and M. Suter, "Network integration of distributed power generation," Journal of Power Sources, 106 (1-2), pp.1-9, 2002.

[124] G. H. Kjølle, I. B. Utne and O. Gjerde, "Risk analysis of critical infrastructures emphasizing electricity supply and interdependencies," Reliability Engineering and System Safety, 105, pp.80-89, 2012.

[125] L. Chang and Z. Wu, "Performance and reliability of electrical power grids under cascading failures," Electrical Power and Energy Systems, 33 pp.1410-1419, 2011.

[126] H. Ren, I. Dobson and B. A. Carreras, "Long-term effect of the n-1 criterion on cascading line outages in an evolving power transmission grid," IEEE Transactions on Power Systems, 23 (3), pp.1217-1225, 2008.

[127] L. Layton, "Electric system reliability indices," web site: http://iiee.org.ph/wp-content/uploads/2015/06/Distribution-System-Reliability-Improvement-2015-IIEE-MYC.pdf, 2004.

[128] M. Čepin, "Distribution and Transmission System Reliability Measures," Assessment of Power System Reliability, Chapter 14, pp.215-226, 2011.

[129] L. Haarla, U. Pulkkinen and M. Koskinen, "A method for analysing the reliability of a transmission grid," Reliability Engineering & System Safety, 93 (2), pp.277-287, 2006.

[130] P. Henneaux, P. E. Labeau and J. C. Maun, "Blackout Probabilistic Risk Assessment and Thermal Effects: Impacts of Changes in Generation," IEEE Transactions on Power Systems, 28 (4), pp. 4722-4731, 2013.

[131] P. Henneaux, P. E. Labeau and J. C. Maun, "A level-1 probabilistic risk assessment to blackout hazard in transmission power systems," Reliability Engineering and System Safety, 102, pp.41-52, 2012.

[132] A. N. Celik, "Effect of different load profiles on the loss-of load probability of stand-alone photovoltaic systems," Renewable Energy, 32 (12), pp.2096-2115, 2007.

[133] C. V. T. Cabral, D. O. Filho, A. S. A. C. Diniz, J. H. Martins, O. M. Toledo, B. L. de Vilhena and M. Neto, "A stochastic method for stand-alone photovoltaic system sizing," Solar Energy,

84 (9), pp.1628-1636, 2010.

[134] I. Abouzahr and R. Ramakumar, "Loss of power supply probability of stand alone photovoltaic systems: a closed form approach," IEEE Transactions on Energy Conversion, 6 (1), pp.1-11, 1991.

[135] K. Mulder, "The dynamics of public opinion on nuclear power. Interpreting an experiment in the Netherlands," Technological Forecasting and Social Change, 79 (8), pp.1513-1524, 2012.

[136] Tokyo Electronic Company, "Tokyo electronic company press release," http://www.tepco.co.jp//cc/press/index1103-j.html (accessed 15/8/2015), 2011.

[137] IEA, "World Energy Outlook 2006," www.worldenergyoutlook.org/ accessed on 19. 3. 20015, 2006.

[138] IAEA, "Energy, Electricity and Nuclear Power Estimates for the Period up to 2050," http://www-pub.iaea.org/MTCD/Publications/PDF/RDS-1-33_web.pdf, 2013.

[139] International Institute for Applied Systems Analysis, "Global Energy Assessment," CAMBRIDGE UNIVERSITY PRESS, chapter 5: Energy and security pp.327, 2012.

[140] F. Y. Hu, C. H. Yeung, S. Yang, W. P. Wang and A. Zeng, "Recovery of infrastructure networks after localised attacks," Scientific Reports, 6, 24522, 2016.

[141] G. Hazi, D. Bică and A. Hazi, "Considerations on an Indicator Guaranteed in the Electricity Supply to Consumers," Procedia Technology, 19, pp.643-650, 2015.

[142] J. Portugal-Pereira and M. Esteban, "Implications of paradigm shift in Japan's electricity security of supply: a multi-dimensional indicator assessment," Applied Energy, 123, pp. 424-434, 2014.

[143] S. H. Lesbirel, "Diversification and energy security risks: the Japanese case," Japanese Journal of Political Science, 5 (1), pp.1-22, 2004.

[144] A. E. Farerell, H. Zerriffi and H. Downlatabadi, "Energy Infrastructure and security," Annu. Rev. Environ. Resour., 24, pp.421-469, 2004.

[145] F. H. Norris, S. P. Stevens, B. Pfefferbaum, K. F. Wyche and R. L. Pfefferbaum, "Community Resilience as a Metaphor, Theory, Set of Capacities, and Strategy for Disaster Readines," Am J Community Psychol, 41, pp.127-150, 2008.

[146] Kansai Electric Company, "energy best mix," KEPCO web site: http://www.kepco.co.jp/corporate/energy/nuclear-power/nowenergy/bestmix.html (accessed on 31/8/2015).

[147] S. Kosai and C. Tan, "Quantitative analysis on a zero energy building performance from

energy trilemma perspective," Sustainable Cities and Society, 32, pp. 130-141, 2017.

[148] METI, " peak demand in summer," http://www.meti.go.jp/setsuden/20110513taisaku/16.pdf (accessed 29/8/2015), 2011.

[149] N. Lefevre, "Measuring the energy security implications of fossil fuel resource concentration," Energy Policy, 38, pp.1635-1644, 2010.

[150] G. Cohen, F. Joutz and P. Loungani, "Measuring energy security: trends in the diversification of oil and natural gas supplies," Energy Policy, 39, pp.4860-4869, 2011.

[151] World Nuclear News (WNN), "Approvals in place for Ikata 3 restart," available at web site: http://www.world-nuclear-news.org/RS-Approvals-in-place-for-Ikata-3-restart-2004166.html (accessed 12.5.2016), 2016.

[152] C. W. Ajan, S. S. Ahmed, A. H. B., F. Taha and A. A. B. Mohd Zin, "On the policy of photovoltaic and diesel generation mix for an off-grid site: East Malaysian perspectives," Solar Energy, 74, pp.453-467 (2003), 2003.

[153] World Bank, "Access to electricity," Global electrification database, World Bank, web site: http://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?end=2012&start=1990 (accessed 07/12/2016), 2012.

[154] A. Q. Jakhrani, A. K. Othman, A. R. H. Rigit and S. R. Samo, "Assessment of solar and wind energy resources at five typical locations in Sarawak," Journal of Energy & Environment, 4(1), pp.1-6, 2012.

[155] J. Laustsen, "Energy Efficiency Requirements in Building Codes," in: energy Efficiency Policies for New Building, OECD/IEA, Paris, 2008.

[156] K. Voss, E. Musall and M. Lichtmeß, "From low energy to net zero energy building: status and perspectives," Green Build, 6, pp. 46–57, 2011.

[157] S. Deng, R. Z. Wang and Y. J. Dai, "How to evaluate performance of net zero energy building - A literature research," Energy, pp.1-16, 2014.

[158] D. Crawley, S. Pless and P. Torcellini, "Getting to net zero," ASHRAE Journal, 51, 9, pp.18-25, 2009.

[159] B. Vale and R. Vale, "The New Autonomous House: Design and Planning for Sustainability," Thames & Hudson Ltd, 2002.

[160] W. Feist, "Life-cycle energy analysis: Comparison of low-energy house, passive house and self-sufficient house," Proceedings of the International Symposium of CIB W67, Vienna, Austria, 1997.

[161] N. Saxena, I. Hussain, B. Singh and A. L. Vyas, "Implementation of a Grid-Integrated PV-Battery System for Residential and Electrical Vehicle Applications," IEEE Transactions on Industrial Electronics, 65 (8), pp.6592-6601, 2018.

[162] M. Arbabzadeh, J. X. Johnson, G. A. Keoleian, P. G. Rasmussen and L. T. Thompson, "Twelve Principles for Green Energy Storage in Grid Applications," Environmental Science & Technology, 50 (2), pp.1046-1055, 2016.

[163] T. Khatib, A. Mohamed and P. Sopian, "A review of photovoltaic systems size optimization techniques," Renewable and Sustainable Energy Reviews, 22, pp.454-465, 2013.

[164] PIA, "Damages of system," available at: http://j-pia.or.jp/test/case.html (in Japanese) (accessed on 30.9.2018), 2013.

[165] D. Stewart, "Habitat and ecology: the cohousing experiment in the United States," Revue française d'études americaines, 94, pp.113-127, 2002.

[166] Ministry of Economy, Trade and Industry (METI), "ZEH load map," available at: http://www.meti.go.jp/press/2015/12/20151217003/20151217003-1.pdf (accessed 27.5.2015), 2015.

[167] H. N. Post and M. G. Thomas, "Photovoltaic systems for current and future applications," Solar Energy, 41 (5), pp.456-473, 1998.

[168] Ministry of Economy, Trade and Industry (METI), "peak demand in summer," http://www.meti.go.jp/setsuden/20110513taisaku/16.pdf (accessed 29/8/2015), 2011.

[169] New Energy and Industrial Technology Development Organization (NEDO), "NEDO irradiation data base," available at: http://app0.infoc.nedo.go.jp/metpv/metpv.html (accessed 8.July.2016), 2016.

[170] N. Skandalos and D. Karamanis, "PV glazing technologies," Renewable and Sustainable Energy Reviews, 49, pp.306-322, 2015.

[171] H. Chen, T. Cong, W. Yang, C. Tan, Y. Li and Y. Ding, "Progress in electrical energy storage system: A critical review," Progress in Nature Science, 19, pp.291-312, 2009.

[172] J. Byrne, A. Zhou, B. Shen and K. Hughes, "Evaluating the potential of small-scale renewable energy options to meet rural livelihoods needs: A GIS- and lifecycle cost-based assessment of Western China's options," Energy Policy, 35, 8, pp.4391-4401, 2007.

[173] International Renewable Energy Agency (IRENA), "Renewable Energy Technologies: Cost Analysis Series," IRENA web: https://www.irena.org/DocumentDownloads/Publications/RE_Technologies_Cost_Analysis-BIOMASS.pdf (accessed 27 August 2016), 2012.

[174] F. Mayr and H. Beushausen, "How to determine meaningful, comparable costs of energy storage," APRICUM web site: http://www.apricum-group.com/how-to-determine-meaningful-comparable-costs-of-energy-storage/ (accessed 9.12.2016), 2016.

[175] International Renewable Energy Agency (IRENA), "Battery Storage For Renewables: Market Status And Technology Outlook," web site: http://www.irena.org/documentdownloads/publications/irena_battery_storage_report_2015.pdf (accessed 22.10.2016), 2015.

[176] B. K. Sovacool and M. A. Brown, "Competing dimensions of energy security: an international perspective," Annu Rev Environ Resour 35, pp.77-108, 2010.

[177] J. Martchamadol and S. Kumar, "Thailand's energy security indicators," Renewable Sustainable Energy Review, 16, pp.6103-6122, 2012.

[178] S. Sharifuddin, "Methodology for quantitatively assessing the energy security of Malaysia and other southeast Asian countries," Energy Policy, 65, pp.574-582, 2014.

[179] C. Curry, "Lithium-ion Battery Costs and Market," available at: https://data.bloomberglp.com/bnef/sites/14/2017/07/BNEF-Lithium-ion-battery-costs-and-market.pdf (accessed 16.8.2018), 2016.

[180] National Renewable Energy Laboratory, "U.S. Solar Photovoltaic System Cost Benchmark," National Renewable Energy Laboratory, 2017.

[181] W. W. Cooper, L. M. Seiford and K. Tone, "Data envelopment analysis. A comprehensive text with models, applications, references and DEA-Solver software," 2nd ed. Springer: New York., 2007.

[182] A. Charnes, W. W. Cooper and E. Rhodes, "Measuring the efficiency of decision making units," European Journal of Operational Research, 2(6), pp.429-444, 1978.

[183] K. Cullinane, T. Wang, D. W. Song and P. Ji, "The technical efficiency of container ports: Comparing data envelopment analysis and stochastic frontier analysis," Transportation Research Part A: Policy and Practice, 40(4), 354-374, 2006.

[184] I. Sartori, A. Napolitano and K. Voss, "Net zero energy buildings: A consistent definition framework," Energy and Building, 48, pp.220-232, 2012.

[185] Federation of Electric Power Companies of Japan, "The Electric Power Industry in Japan 2018," available at: https://www.jepic.or.jp/en/data/japan_data.pdf (accessed 7.8.2018), 2018.

[186] C. P. Nguyen and A. J. Flueck, "Agent based restoration with distributed energy storage support in smart grids," IEEE Transactions on Smart Grid, 3 (2), pp.1029-1038, 2012.

[187] R. Shankar, K. Chatterjee and R. Bhushan, "Impact of energy storage system on load

frequency control for diverse sources of interconnected power system in deregulated power environment," International Journal of Electrical Power & Energy Systems, 79, pp.11-26, 2016.

[188] X. N. Wang, N. H. El-Farra and A. Palazoglu, "Optimal scheduling of demand responsive industrial production with hybrid renewable energy systems," Renewable Energy, 100, pp.53-64, 2017.

[189] R. Atia and N. Yamada, "Sizing and Analysis of Renewable Energy and Battery Systems in Residential Microgrids," IEEE Transactions on Smart Grid, 7 (3), pp.1204-1213, 2016.

[190] X. N. Wang, A. Palazoglu and N. H. El-Farra, "Operational optimization and demand response of hybrid renewable energy systems," Applied Energy, 143, pp.324-335, 2015.

[191] Y. F. Wang, I. R. Pordanjani and W. Xu, "An Event-Driven Demand Response Scheme for Power System Security Enhancement," IEEE Transactions on Smart Grid, 2 (1), pp.23-29, 2011.

[192] R. Billinton and R. N. Allan, "Power-system reliability in perspective," Electronics & Power, 30, pp.231–236, 1984.

[193] R. Billinton and L. Gan, "Use of Monte Carlo simulation in teaching generating capacity adequacy assessment," IEEE Transactions on Power Systems, 6 (4), pp.1571–1577, 1991.

[194] E. S. Hrayshat, "Techno-economic analysis of autonomous hybrid photovoltaic-diesel-battery system," Energy for Sustainable Development, 13 (3), pp. 143-150, 2009.

[195] M. Mohammadi, R. Ghasempour, F. R. Astaraei, E. Ahmadi, A. Aligholian and A. Toopshekan, "Optimal planning of renewable energy resource for a residential house considering economic and reliability criteria," International Journal of electrical Power & Energy Systems, 96, pp.261-273, 2018.

[196] M. Chaudry, J. Z. Wu and N. Jenkins, "A sequential Monte Carlo model of the combined GB gas and electricity network," Energy Policy, 62, pp.473-483, 2013.

[197] D. Suchitra, R. Jegatheesan and T. J. Deepika, "Optimal design of hybrid power generation system and its integration in the distribution network," International Journal of Electrical Power & Energy Systems, 82, pp.136-149, 2016.

[198] B. K. Das, Y. M. Al-Abdeli and G. Kothapalli, "Optimisation of stand-alone hybrid energy systems supplemented by combustion-based prime movers," Applied Energy, 196, pp.18-33, 2017.

[199] B. Alinejad, M. Fotuhi-firuzabad and M. Parvania, "Composite system well-being analysis using sequential Monte Carlo simulation And fuzzy algorithm," IU-Journal of Electrical & Electronics Engineering, 13 (1), pp.1575-1580, 2013.

[200] S. Mandelli, C. Brivio, E. Colombo and M. Merlo, "Effect of load profile uncertainty on the optimum sizing of off-grid PV systems for rural electrification," Sustainable Energy Technologies and Assessments, 18, pp.34-47, 2016.

[201] J. Kramer, A. Krothapalli and B. Greska, "The Off-grid Zero Emission Building," in: Energy Sustainability Conference, Long Beach, California, 2007.

[202] P. Hermandez and P. Kenny, "From net energy to zero energy building: Defining life cycle zero energy building," Energy and Buidings, 42, 6, pp.815-821, 2010.

[203] I. Nolte, O. Ralf, D. Staniaszek and M. Faber, "Implementing the Cost Optimal Methodology in EU Countries," Report published by the Buildings Performance Institute Europe (BPIE), http://bpie.eu/wp-content/uploads/2015/10/Implementing_Cost_Optimalit, 2013.

[204] M. Hamdy, A. Hasan and K. Siren, "A multi-stage optimization method forcost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010," Energy and Building, 56, pp.189–203, 2013.

[205] K. B. Lindberg, G. Doorman, D. Fischer, M. Korpås, A. Ånestad and I. Sartori, "Methodology for optimal energy system design of Zero Energy Buildings using mixed-integer linear programming," Energy and Building, 127, pp.194-205, 2016.

[206] S. Cao and K. Siren, "Matching indices taking the dynamic hybrid electrical and thermal grids information into account for the decision-making of nZEB on-site renewable energy systems," Energy Conversion and Management, 101, pp.423-441, 2015.

[207] L. Georges, C. Massart, G. Moeseke and A. De Herde, "Environmental and economic performance of heating systems for energy-efficient dwellings: case of passive and low-energy single-family houses," Energy Policy, 40 (1), pp.452–464, 2012.

[208] H. Ren and W. Gao, "Economic and environmental evaluation of micro CHP systems with different operating modes for residential buildings in Japan," Energy and Buildings, 42 (6), pp.853–861, 2010.

[209] H. Huws and L. Jankovic, "A method for zero carbon design using multi-objective optimization," On Proceedings of the 1st International Conference on Zero Carbon Building Today and in the Future, Birmingham City University pp.99-106 http://www.ljubomirjankovic.com/papers/p1129_final.pdf, 2014.

[210] J. Salom, A. J. Marszal, J. Widen, J. Candanedo and K. B. Lindberg, "Analysis of load match and grid interaction indicators in net zero energy buildings with simulated and monitored data," Applied Energy, 136, pp.119-131, 2014.

[211] B. Verbruggen and J. Driesen, "Grid Impact Indicators for Active Building Simulations," IEEE Transactions on Sustainable Energy, 6 (1), pp.43-50, 2015.

[212] M. Mehrabankhomartash, M. Rayati, A. Sheikhi and A. M. Ranjbar, "Practical battery size optimization of a PV system by considering individual customer damage function," Renewable & Sustainable Energy Reviews, 67, pp.36-50, 2017.

[213] J. Renau, L. Domenech, V. García, A. Real, N. Montés and F. Sánchez, "Proposal of a nearly zero energy building electrical power generator with an optimal temporary generation–consumption correlation," Energy and Buildings, 83, pp.140-148, 2014.

[214] S. Gangwar, D. Bhanja and A. Biswas, "Cost, reliability, and sensitivity of a stand-alone hybrid renewable energy system-A case study on a lecture building with low load factor," Journal of Renewable and Sustainable Energy, 7 (1), 013109, 2015.

[215] R. Ayop, N. M. Isa and C. W. Tan, "Components sizing of photovoltaic stand-alone system based on loss of power supply probability," Renewable & Sustainable Energy Reviews, 81, pp.2731-2743, 2018.

[216] V. N. Kostas, A. N. Platis and N. S. Sapidis, "Performability assessment of standalone photovoltaic residential systems," International Journal of Performability Engineering, 12 (5), pp.485-500, 2016.

[217] I. S. Saeh, M. W. Mustafa, Y. S. Mohammed and M. Almaktar, "Static Security classification and Evaluation classifier design in electric power grid with presence of PV power plants using C-4.5," Renewable & Sustainable Energy Reviews, 56, pp.283-290, 2016.

[218] J. Hazra and A. K. Sinha, "A risk based contingency analysis method incorporating load and generation characteristics," International Journal of Electrical Power & Energy Systems, 32 (5), pp.433-442, 2010.

[219] X. D. Liu, M. Shahidehpour, Z. Y. Li, X. Liu, Y. J. Cao and Z. H. Bie, "Microgrids for Enhancing the Power Grid Resilience in Extreme Conditions," IEEE Transactions on Smart Grid, 8 (2), pp.589-597, 2017.

[220] L. Haarla, U. Pulkkinen, M. Koskinen and J. Jyrinsalo, "A method for analysing the reliability of a transmission grid," Reliability Engineering & System Safety, 93 (2), pp.277-287, 2008.

[221] L. F. Rocha, C. L. T. Borges and G. N. Taranto, "Reliability Evaluation of Active Distribution Networks Including Islanding Dynamics," IEEE Transactions on Power Systems, 32 (2), pp.1545-1552, 2017.

[222] A. Abu-Siada, N. Hashemnia, S. Islam and M. A. S. Masoum, "Understanding Power Transformer Frequency Response Analysis Signatures," IEEE Electrical Insulation Magazine, 29 (3), pp.48–56, 2013.

[223] X. Zhao, C. Yao, Z. Zhao and A. Abu-Siada, "Performance evaluation of online transformer internal fault detection based on transient overvoltage signals," IEEE Transactions on

Dielectrics and Electrical Insulation, 24 (6), pp.3906-3915, 2017.

[224] S. Datta and V. Vittal, "Operational Risk Metric for Dynamic Security Assessment of Renewable Generation," IEEE Transactions on Power Systems, 32 (2), pp.1389-1399, 2017.

[225] D. You, K. Wang, L. Ye, J. Wu and R. Huang, "Transient stability assessment of power system using support vector machine with generator combinatorial trajectories inputs," International Journal of Electrical Power & Energy Systems, 44 (1), pp.318-325, 2013.

[226] D. S. Kirschen, D. Jayaweera, D. P. Nedic and R. N. Allan, "A probabilistic indicator of system stress," IEEE Transactions on Power Systems, 19, (3), pp.1650-1657, 2004.

[227] P. Henneaux, P. E. Labeau, J. C. Maun and L. Haarla, "A Two-Level Probabilistic Risk Assessment of Cascading Outages," IEEE Transactions on Power Systems, 31 (3), pp.2393-2403, 2016.

[228] J. D. McCalley, A. A. Fouad, V. Vittal, A. A. Irizarry-Rivera, B. L. Agrawal and R. G. Farmer, "A risk-based security index for determining operating limits in stability-limited electric power systems," IEEE Transactions on Power Systems, 12 (3), pp.1210-1219, 1997.

[229] A. Dissanayaka, U. D. Annakkage, B. Jayasekara and B. Bagen, "Risk-Based dynamic security assessment," IEEE Transactions on Power System, 26 (3), pp.1302-1308, 2011.

[230] M. Abapour and M. R. Haghifam, "On-line assessment of the transient instability risk," IET Generation, Transmission, Distribution, 7 (6), pp.602-612, 2013.

[231] X. Yu and C. Singh, "A practical approach for integrated power system vulnerability analysis with protection failures," IEEE Transactions on Power Systems, 19 (4), pp.1811-1820, 2004.

[232] M. Panteli and M. Pierluigi, "Influence of extreme weather and climate change on the resilience of power systems: Impacts and possible mitigation strategies," Electric Power Systems Research, 127, pp. 259–270, 2015.

[233] R. Rocchetta and E. Patelli, "Assessment of power grid vulnerabilities accounting for stochastic loads and model imprecision," International Journal of Electrical Power and Energy Systems, 98, pp.219-232, 2018.

[234] R. Arghandeh, A. von Meier, L. Mehrmanesh and L. Mili, "On the definition of cyber-physical resilience in power systems," Renewable & Sustainable Energy Reviews, 58, pp.1060–1069, 2016.

[235] M. Zare-Bahramabadi, A. Abbaspour, M. Fotuhi-Firuzabad and M. Moeini-Aghtaie, "Resilience-based framework for switch placement problem in power distribution systems," IET Generation Transmission & Distribution, 12 (5), pp.1223-1230, 2018.

[236] X. D. Liu, M. Shahidehpour, Y. J. Cao, Z. Li and W. Tian, "Risk assessment in extreme events

considering the reliability of protection systems," IEEE Transactions on Smart Grid, 6 (2), pp.1073-1081, 2015.

[237] G. F. Li, P. Zhang, P. B. Luh, W. Y. Li, Z. H. Bie, C. Serna and Z. B. Zhao, "Risk analysis for distribution systems in the Northeast U.S. under wind storms," IEEE Transactions on Power Systems, 29 (2), pp.889-898, 2014.

[238] M. Roach, "Community power and fleet microgrids: Meeting climate goals enhancing system resilience and stimulating local economic development," IEEE Electrification Magazine, 2 (1), pp.40-53, 2014.

[239] M. Simonov, "Dynamic partitioning of DC microgrid in resilient clusters using event-driven approach," IEEE Transactions on Smart Grid, 5 (5), pp.2618–2625, 2014.

[240] M. Panteli and P. Mancarella, "The Grid: Stronger, Bigger, Smarter?: Presenting a Conceptual Framework of Power System Resilience," IEEE Power and Energy Magazine, 13 (3), pp.58-66, 2015.

[241] M. Panteli, C. Pickering, S. Wilkinson, R. Dawson and P. Mancarella, "Power System Resilience to Extreme Weather: Fragility Modeling, Probabilistic Impact Assessment, and Adaptation Measures," IEEE Transactions on Power Systems, 32 (5), pp.3747-3757, 2017.

[242] C. Chen, J. Wang, F. Qiu and D. B. Zhao, "Resilient Distribution System by Microgrids Formation After Natural Disasters," IEEE Transactions on Smart Grid, 7 (2), pp.958–966, 2016.

[243] Z. Wang and J. Wang, "Self-healing resilient distribution systems based on sectionalization into microgrids," IEEE Transactions on Power System, 30 (6), pp.3139–3149, 2015.

[244] J. A. Peças Lopes, C. L. Moreira and A. G. Madureira, "Defining control strategies for MicroGrids islanded operation," IEEE Transactions on Power Systems, 21 (2), pp.916-924, 2006.

[245] N. Nikmehr and N. Sajad, "Optimal operation of distributed generations in micro-grids under uncertainties in load and renewable power generation using heuristic algorithm," IET Renewable Power Generation 9, (8), pp. 982–990, 2015.

[246] H. Farzin, M. Fotuhi-Firuzabad and M. Moeini-Aghtaie, "Enhancing Power System Resilience Through Hierarchical Outage Management in Multi-Microgrids," IEEE Transactions on Smart Grid, 7 (6), pp.2869-2879, 2016.

[247] Y. Wang, C. Chen, J. Wang and R. Baldick, "Research on resilience of power systems under natural disasters—A review," IEEE Transactions on Power Systems, 31 (2), pp.1604-1613, 2016.

[248] R. Rocchetta, E. Zio and E. Patelli, "A power-flow emulator approach for resilience

assessment of repairable power grids subject to weather-induced failures and data deficiency," Applied Energy, 210, pp.339-350, 2018.

[249] M. Panteli, D. N. Trakas, P. Mancarella and N. D. Hatziargyriou, "Boosting the Power Grid Resilience to Extreme Weather Events Using Defensive Islanding," IEEE Transactions on Smart Grid, 7 (6), pp.2913-2922, 2016.

List of publication

Peer-reviewed international journals

Shoki Kosai, ChiaKwang Tan, Eiji Yamasue Evaluating Power Reliability Dedicated for Sudden Disruptions: Its Application to Determine Capacity Size on a Basis of Energy Security, sustainability, 10 (6), 2059 ***(Chapter 3)*** [2018]

Shoki Kosai, Hironobu Unesaki, Quantitative Analysis on the Impact of Nuclear Energy Supply Disruption on Electricity Supply Security, Applied Energy, 208, pp.1198-1207 ***(Chapter 4)*** [2017]

Shoki Kosai, Eiji Yamasue, Cost-Security Analysis Dedicated for Off-Grid Electricity System, Renewable Energy, 115, pp.871-879 ***(Chapter 5)*** [2018]

Shoki Kosai, Jordi Cravioto, Resilience of standalone hybrid renewable energy systems: the role of storage capacity, Energy, 196, 117133 ***(Chapter 5)*** [2020]

Shoki Kosai, Dynamic Vulnerability in Standalone Hybrid Renewable Energy System, Energy Conversion and Management, 180, pp. 258-268 ***(Chapter 6)*** [2019]

Shoki Kosai, Hironobu Unesaki, Short-term vs long-term reliance: Development of a novel approach for diversity in power mix in energy security, Applied Energy, 262, 114520 ***(Chapter 3, 6, 7)*** [2020]

Shoki Kosai, Hironobu Unesaki, Conceptualizing maritime security for energy transportation security, Journal of Transportation Security, Volume 9, Issue 3, pp.175-190 [2016]

Shoki Kosai, ChiaKwang Tan, Quantitative analysis on a zero energy building performance from energy trilemma perspective, Sustainable Cities and Society, Volume 32, pp.130-141 [2017]

Shoki Kosai, Seiji Hashimoto, Kazuyo Matsubae, Benjamin McLellan, Eiji Yamasue, Comprehensive Analysis of External Dependency in terms of Material Criticality by Employing Total Material Requirement: Sulfuric Acid Production in Japan as a case study, minerals, Volume 8, Issue 3, 114 [2018]

Shoki Kosai, Masaki Nakanishi, Eiji Yamasue, Vehicle Energy Efficiency Evaluation from Well-to Wheel Lifecycle Perspective, Transportation Research Part D: Transport and Environment, 65, pp.355-367 [2018]

Shoki Kosai, Eiji Yamasue, Global warming potential and total material requirement in metal production: Identification of changes in environmental impact through metal substitution, Science of the Total Environment, 651, pp.1764-1775 [2019]

Shoki Kosai, Eiji Yamasue, Recommendation to ASEAN nuclear development based on lessons learnt from the Fukushima nuclear accident, Energy Policy, 129, pp.628-635 [2019]

Wataru Miyamoto, Shoki Kosai, Seiji Hashimoto, Evaluating Metal Criticality for Low-Carbon Power Generation Technologies in Japan, minerals, Volume 9, Issue 2, 95 [2019]

Nobuyuki Mizuno, Shoki Kosai, Eiji Yamasue, Applicability of Wiedemann-Franz Law to Thermal Conductivity of Molten Field's Metal, Materials Science Forum, 985, pp.1-9 [2020]

Shoki Kosai, Yusuke, Kishita, Eiji Yamasue, Estimation of the metal flow of WEEE in Vietnam Considering Lifespan Transition, Resources, Conservation & Recycling, 154, 104621 [2020]

Shoki Kosai, Muku Yuasa, Eiji Yamasue, Chronological Transition of Relationship between Intracity Lifecycle Transport Energy Efficiency and Population Density, energies, 13, 2094 [2020]

Shoki Kosai, Hironobu Unesaki, Quantitative Evaluation of Nuclear Energy Supply Security: United States as a Case Study, Energy Strategy Review 29, 100491 [2020]

International conference

Shoki Kosai, N. A. Rahim, Energy mix with the vulnerability of nuclear power utilization, Proceeding in 4th IET International Conference on Clean Energy and Technology CEAT 2016, 14-15 November 2016, Kuala Lumpur, Malaysia [2016]

Shoki Kosai, ChiaKwang Tan, Cost Benefit Analysis for ZEB: Optimal Capacity Based on Reliability, Economy and Diversification, Proceeding in 5th IET International Conference on Clean Energy and Technology CEAT 2018 [2018]

Eiji Yamasue, Shoki Kosai, Benjamin C McLellan, Shinsuke Murakami, Seiji Hashimoto,Resource Paradox Problem revealed by Total Material Requirement, 13th Society And Materials, International Conference (SAM13), May 20-21, 2019, Pisa, Italy [2019]

Daiki Kurogi, Shoki Kosai, Lai Thai Phong, Nguyen Duc Quang, Eiji Yamasue, Estimation of Lifespan Distribution of Motorcycles in Vietnam, Product Lifetimes and the Environment (PLATE2019), September 18-20, 2019, Berlin, Germany [2019]

Shoki Kosai, Eiji Yamasue, Towards intercity cooperation: Comparison of spatial transport energy efficiency between central and peripheral cities in Japan, EcoDesign2019, November 25-27, 2019, Yokohama, Japan [2019]

Shoki Kosai, Eiji Yamasue, Economy-wide material flow analysis and its projection: DMI vs TMR in Japan, EcoDesign2019, November 25-27, 2019, Yokohama, Japan [2019]

Appendix

System adequacy analysis

Conventional categorization of power system is three operational regions including generation, transmission and distribution [192], which helps to clearly identify the parts of power system assessed in the research. Given that assessments of power system adequacy primarily concerns on the sufficiency of capacity size to meet the total power demand in the system, it has been widely assumed that the transmission and distribution technologies are completely reliable [99]. Adequacy assessments have been developed under two main constituents: the generation facilities and load, matched with the hierarchical level 1 (HL-1) [193].

Earlier research works have conducted adequacy assessments for the various scales of power system. Particularly for distributed network, while the majority is the scale of community-based microgrid, the smaller scale including the individual building and house is also considered [194, 195]. The case of a larger scale of power flow system was also addressed so far (e.g., Chaudry et al. assessed the adequacy of gas network connected to the whole national grid in UK by employing a sequential Monte Carlo simulation [196]), this section only focuses on the adequacy assessment in hybrid renewable energy system.

Community-based microgrids are formulated with the hybrid renewable energy system. Various energy sources have been integrated in the hybrid system including solar photovoltaic (PV), wind, diesel, micro hydro, micro gas, biomass, and biogas. Particularly, solar PV and wind are key sources for the hybrid renewable energy system. Storage technology often represents a battery, which are integrated in the hybrid systems in the most cases for the levelling of intermittency. Meanwhile, some studies (e.g., [73, 79, 71]) did not employ the battery in their hybrid systems.

Most of microgrids assessed in the hybrid renewable energy system are standalone. Standalone microgrids are expected to solve the uneven balance of energy services. 15 % of global population experience energy poverty under no access to electricity [153]. National grids are not fully covered in the remote rural areas due to not being worth investing the extension of grid for an only few residential people [152]. Besides that, given that microgrids are a promising future technology in urban areas, some of authors (e.g., [73, 71, 69]) assessed the microgrids connected to the national grid to assess the adequacy of interconnection. Suchitra et al. [197] conducted the comparative reliability assessment of on-grid and off-grid microgrids.

In most cases, the target span is one year, which is considered long enough for the adequacy assessment. Some authors used the lifetime of hybrid renewable energy technology with 20 years [73], and 25 years of life span [64]. Another study focused on the most vulnerable month in terms of continuous power supply from the past experience [74]. In addition, while hourly model simulation is common, Das et al. assessed the impact of time resolution differences between 15 minutes and 1 hour on the simulation outcomes [198].

In order to take into consideration the intermittent and stochastic nature inherent in renewable energy, a probabilistic method has been basically utilized to estimate the power system reliability. Various probabilistic models have been developed in last few decades [199]. The probabilistic approach was employed not only for power adequacy of hybrid renewable energy system but also grid system security and resilience evaluation. Power system reliability is expressed in the form of various indices [59]. The widely accepted reliability indices are as follows:

Loss of power supply probability (LPSP)	The ratio of summation of energy deficit over the total energy demand during the considered period
Loss of load expectation (LOLE)	The ratio of summation of energy deficit duration over the considered period
Loss of load probability (LOLP)	The probability of supplied power not meeting the demand for the considered period

Expected energy not supplied (EENS)	Expected energy deficiency when the demand is greater over the supply

The different indices for reliability evaluation have been proposed, including deficiency of power supply probability [80], system autonomy [76], percentage of risk and healthy state probability [81], max energy not supplied [82], and loss of load hours [67].

Various research works have focused on uncertainties potentially affecting on reliability assessment in the hybrid renewable energy system. Meteorological and geographical characteristics are one of the major resource uncertainties [70]. Zolfaghari et al. integrated the geographical information at the multiple wind sites in the reliability assessment [71]. Roy et al. conducted sequential Monte Carlo simulation to evaluate the wind speed uncertainty in the chronological series [72]. Energy demand pattern is also considered as a major uncertainty [200]. Semaoui et al. analyzed the impact of energy management on the demand side on the whole reliability assessment and capacity sizing optimization [64]. Several research works evaluated both uncertainties in the reliability assessment covering meteorological factors such as solar irradiation and wind speed and load demand fluctuations (e.g., [67, 77]).

Interest of standalone and grid-connected distributed network has been growing as a major research target for assessing reliability of the hybrid renewable energy system. Meanwhile, an individual building and house as the smaller scale of power supply flow system has been also focused recently in the reliability and size optimization narratives in response to the evolution of zero energy building/home (ZEB/ZEH).

ZEB consumes energy produced on-site with the renewable energy system to meet the energy demand of building [157]. Given the energy loss and capital costs for the installation of storage technology in a standalone ZEB [201], grid-connected ZEB has been given preference in the interest of research [202]. In order to achieve the intended goal of ZEB, the capacity sizing of renewable energy needs to be carefully assessed on a basis of performance evaluation [147]. The ZEB performance is often optimized from the various perspectives including economy [203, 204, 205], environment [206, 207, 208], and comfort [209].

Regardless of whether ZEB is connected to the grid or not, ensuring the continuous electricity supply is of paramount importance. Many research works have conducted the reliability assessment of renewable energy system in ZEB/ZEH.

Pertaining to the grid-connected ZEB, LOLP is utilized to monitor how often power is supplied from the connected grid [210, 211, 212]. Renau et al. evaluated reliability of the nearly ZEB in the form of self-sufficiency by analyzing the annual energy balance [213].

Pertaining to the standalone ZEB and ZEH, Gangwar et al. assessed reliability and sensitivity of hybrid renewable energy system in a lecture building of a technical institute [214]. Ayop et al. computed LPSP of solar PV/battery system of building in Malaysia [215]. Kostas et al. conducted the comparative assessment of loss of energy expectation (LOEE) and LOLE in the solar PV system of a small residence in Greece [216]. Hu and Augenbroe developed the stochastic model for the reliability evaluation in the off-grid solar house in US by proposing various indicators including load-point failure rate, load-point outage duration, load-point annual unavailability, and energy wasted [52].

System security analysis

In contrast to the adequacy of reliability, power system ability to address the sudden disturbances at the dynamic condition is associated with system security and resilience. System security and resilience have been scarcely evaluated in the hybrid renewable energy system, whereas its interest in the case of centralized power grid has been grown as a research topic. In order to achieve the comprehensive reliability assessment for the determination of optimal capacity size in the hybrid renewable energy system in future, this Section surveys the trend of the security and resilience assessment in centralized power grid.

Grid system security has been independently evaluated in the topic of system security assessment [217]. System security indicates the power system ability to withstand sudden disturbances including failures of power system facilities including generators [218], transmission lines [219, 220], distribution lines [221], transformers [222, 223], converters [224]. In order to evaluate the impact of sudden disturbances, transient stability assessment has been widely conducted. Transient stability assessment is highly associated with the system ability to maintain synchronism after the occurrence of severe transient disturbances [225]. In addition, the probabilistic evaluation approaches have been integrated with the transient stability assessment [226]. Benidris et al. introduced the three probabilistic transient stability indices including the system instability, the robustness against fault events and the unstable risk of sudden disturbances [49]. Rocha et al. combined the probabilistic reliability indices including System Average Interruption Frequency, System Average interruption Duration, and EENS with the dynamic islanding operation evaluated by the transient stability assessment [221]. Given the sudden disturbances have a potential of leading to cascading outages, Henneaux et al. developed the probabilistic simulation model for the slow cascades and the fast cascades [227].

In addition to the probabilistic consideration in the security assessment, the impact of failures on the system has been also taken into account in the form of risk-based approach encompassing the likelihood and consequence [228, 229, 230]. Ciapessoni et al. divided the risk into the thorough categorizations including threats, vulnerability, contingency and impact and conducted the risk-based security assessment in the aggregated system of both power flow and Information and

Communication Technology [102]. Hazra and Sinha presented the risk-based security model incorporating the severity of contingencies with the forced outage statistics [218].

Some research works combined both adequacy and security to evaluate the overall system reliability [50, 231]. Lei et al. assessed the reliability of both generation and transmission facilities by employing LOLP to measure adequacy and security [50]. Yu and Singh utilized the different reliability indices separately including Bus Isolation Probability (BIP), Expected Power Loss (EPL) and LOLP for adequacy and Probability of Stability (POS) for security [231].

Globally, the extreme natural disasters have caused the extensive blackout covering the wide range of national grid (e.g., including Hurricane Katrina in 2005, Great East Japan Earthquake in 2011 and Hurricane Sandy in 2012) [232]. The wide range of blackout has a significant impact on the economy and society [233]. Therefore, development of resilient power system is of significant importance to deal with sudden extreme disturbances and to avoid the widespread power supply disruptions.

It must be noted that there is no universal consensus on resilience in the power system communities and the definition of resilience varies from researchers [234]. Given that the concept of resilience is still at its infancy [235], the scope of some researches, which should be matched with system resilience, were sometimes discussed in the reliability and security narratives (e.g., [236, 237]). Compared to the system security, the term "resilience" is used to express the ability of extensive power system to withstand the massive and extreme events including hurricanes, tornados and earthquakes with a low probability [238, 239]. Recovering process, which is mostly ignored in the reliability narrative, is also included in the system resilience analysis [240].

Among the conventional grid categories, transmission and distribution lines are often focused in the resilience assessment. Panteli et al. conducted multi-temporal and multi-regional resilience assessment with application to the impact modelling of severe windstorms on transmission networks based on optimal power flow and sequential Monte Carlo simulation [241]. Particularly, interest in the improvement of transmission and distribution lines against natural disasters with introducing microgrids has been growing as a research topic [242, 243]. Microgrids can operate in islanding mode from the transmission network when occurring extreme events to enhance reliability of power system with supplying the electricity to the local demand [244, 245]. It is important to ensure a successful microgrids islanded operation from the perspectives of not only technical stability but also redundant local generation and storage capacity size [246, 247].

In order to quantify the system resilience, various indices have been utilized. Liu et al. demonstrated the usefulness of microgrids to improve the power system resilience by employing LOLP and EENS [219]. Zare-Bahramabadi et al. developed a new index for quantifying the resilience of distribution systems against extreme weather-related loading by taking into consideration the geographic information system [235]. Rocchetta et al. employed EENS and developed the probabilistic resilience framework incorporating weather-influenced failures and recovery of the system components [248]. EENS was further applied to Resilient Achievement Worth Index to quantify maximum percentage improvement of system resilience [241]. Farzin et al. focused on the expected energy curtailment during disturbances to form a new index to monitor the outage management strategies [246]. Panteli et al. took into account a risk-based islanding algorithm and proposed Severity Risk Index developed based on the magnitude and probability in the failure scenarios [249]. Li et al. employed the traditional reliability indices including System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), Average Service Availability Index (ASAI), besides EENS [237].