

博士論文

STUDY ON THE LIMITATION OF RENEWABLE ENERGY PERFORMANCE
AND ITS IMPACT ON PUBLIC GRIDS UNDER DIFFERENT POWER SUPPLY
SYSTEM

再生可能エネルギーの導入における地域の受入限界や
系統電力への影響に関する研究

2022 年 02 月

徐 婷婷

XU TINGTING

Study on the Limitation of Renewable Energy Performance and Its Impact on the Public Grids Under Different Power Supply System

ABSTRACT

In the context of energy shortages and safe supply requirements, renewable energy has been developing steadily in recent years. Among them, the power sector plays an important role in energy conservation and emission reduction. The development of renewable energy can not only reduce the use of fossil energy, but also increase the rate of energy self-sufficiency. Japan's current energy self-sufficiency rate is only 8%. After the implementation of the FiT system in 2011, renewable energy has experienced explosive growth. Among them, PV and wind energy have shown a leading position in growth. Photovoltaic and wind energy are also called variable renewable energy because of their variable power generation characteristics. Their large-scale introduction affects the stability of the grid, so this research is dedicated to studying the interaction between renewable energy, power demand, grid, and energy storage system to maximize the use of VRE.

In Chapter 1, RESEARCH BACKGROUND AND PURPOSE OF THE STUDY. The research backgrounds of energy resources are introduced in Chapter1, which is including the current status and bottleneck of integrational energy development. As well as the significant of developing variable renewable energy. Then, the development and status of renewable energy in world and Japan is well introduced. It is essential to developing renewable energy in the power generation sector to dealing with the problem of energy security and fossil fuel shortage. At last, the research purpose and logical framework is shown in order to support reviewers understand the content of this paper.

In Chapter 2, LITERATURE REVIEW OF VARIABLE AND RENEWABLE ENERGY. The relevant research of this paper is well reviewed in this Chapter. The development of renewable energy in power systems, including the variable renewable energy studies and its hybrid with pumped storage system studies. Besides, the evaluation indicator used in this paper is also well explained further. At lase, the energy management tool of EnergyPLAN models is reviewed. According to the previously study, the current paper contributes to combined them and promote it in the integration potential of renewable energy.

In Chapter 3, METHODOLOGY. The keyword of this paper is load in demand side, electricity generator in supply side, power grid, and storage system. Therefore, the methodology employed including, evaluation indicators of VRE on the power grid, PHS installed capacity prediction, and EnergyPLAN model are summarized in Chapter 3. It helps us to understand the interplay of load in demand side, electricity generator in supply side, power grid, and storage system to seek a ideal electricity production compositions.

In Chapter 4, DATA RESOURCE AND ENERGY CONVERSION ANALYSIS. The data resource mainly focus on the distribution of research area, the composition of power generation in research area, electricity production profiles, and economic cost. Kyushu, Tokyo, Kansai, and Hokkaido with different power proportions, electricity demand profiles, and renewable energy resources are selected to compared and analysis. The energy conversion of fossil fuel to renewable energy is adopted whist.

In Chapter 5, ASSESSMENT OF RENEWABLE ENERGY INTEGRATION IN SUPPLY SIDE. This chapter evaluated the impact of PV and wind on the public electricity supply system when they are introduced into the grid. A method of predict the maximum penetration of renewable energy and its impact on the public electricity supply system is explained in Chapter 3, which is capacity credit and dynamic investment payback period. The results indicate that the capacity credit increases with an increase in PV and wind shares in the grid. However, it seems to be saturated when the share of PV and wind power in the grid reaches 25% and 60%, respectively. Compared with the wind integration in Kansai and Hokkaido, the PV penetration in Kyushu and Tokyo reaches saturation more rapidly. In addition, PV shows more power suppression, which prolongs its payback period compared to wind energy. The significant difference in the results of capacity credit and DIPP is limited by the characteristics of power demand in mixed regions and the relevance of renewables distribution.

In Chapter 6, ASSESSMENT OF DEMAND SIDE IN VRE INTEGRATION. The impact of a reduction in load demand on renewable energy in the Japan public power grid under a state of emergency declaration (April to May 2020) is compared. Research area is distributed in Kyushu, Tokyo, Kansai, and Hokkaido. The results are shown that the consumption profiles and amounts of power consumption reduction are different in different areas. Tokyo shows the largest share of reduced load, followed by Kansai, Kyushu, and Hokkaido. The load reduction was mainly seen during the day, which reflects the differences in people's activities relative to the same period in 2019. Different means of power dispatch, including power generators, energy storage systems, and transmission lines are used and compared in terms of responses to the changes in electricity consumption profile. Besides, the overall fall in total load demand and the change in load sequence affected the integration and curtailment of PV power generation and consequentially caused the electricity price to drop. This Chapter clarifies the effects of COVID-19 on the public power grids of Japan. Further, it establishes the impact on policymakers in relation to the development of renewable energy.

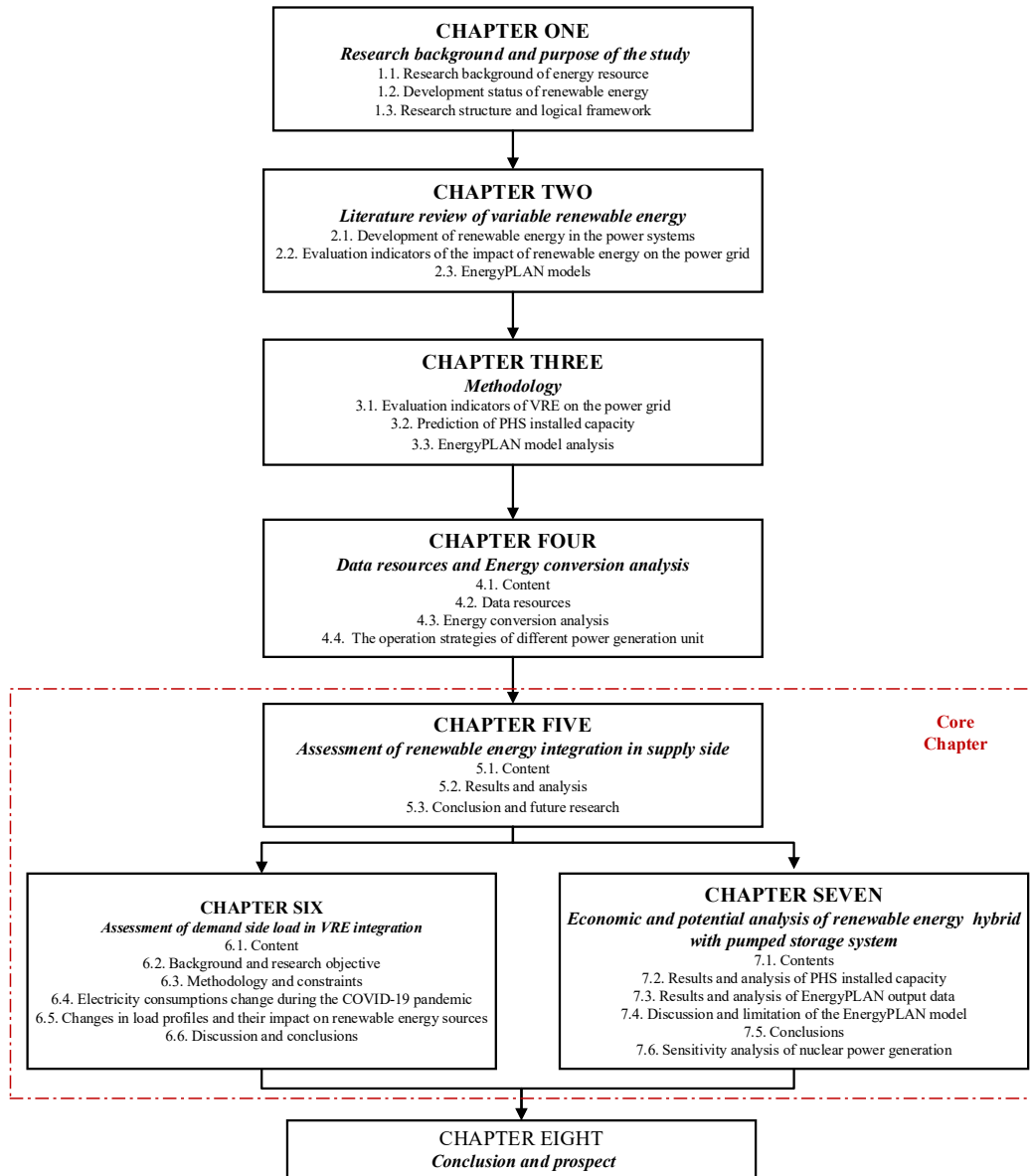
In Chapter 7, ECONOMIC AND POTENTIAL ANALYSIS OF RENEWABLE ENERGY HYBRID WITH PUMPED STORAGE SYSTEM. The pumped storage system is used in the energy management system in order to promote the integration of renewable energy integrations. the existing small and medium-size dams in Japan is exploited to expend the capacity of PHS installed.

Combining with the phase-out of thermal power, analyze the basic load power supply equipment contributes to regional VRE penetration. Its energy conversion analysis is introduced in Chapter 3. Kyushu and Hokkaido power grids with different power generation structure and electricity demand profiles as case study. Scenario settings are based on hourly power demand and supply curves using the EnergyPLAN tool. The result shown that the installed capacity potential of small and medium-sized pumped storage in Kyushu and Hokkaido is 18GW and 20GW, respectively. PHS can reduce RES suppression and thermal power operation while providing a share of grid stability. The reduction of the initial installation of thermal power improves the penetration of RES and the operation rate of PHS. the average power generation cost decreases with the reduction of thermal power installation capacity. Besides, the addition of PHS is first higher and then lower than the scenario without energy storage equipment. Under the same RES share, the maximum cost of Kyushu is 16yen / kWh and that of Hokkaido is 26yen / kWh. Attributed to the nuclear power in Kyushu, which accounts to 25% share of power generation. The penetration of VRE in the future public grid and its impact on other power generation units are covered.

In Chapter 8, CONCLUSION AND PROSPECT. A summarized of each Chapter is concluded.

徐 婷婷 博士論文の構成

Study on the Limitation of Renewable Energy Performance and Its Impact on the Public Grids Under Different Power Supply System



CONTENTS

ABSTRACT	I
STRUCTURE OF THIS PAPER	IV
 CHAPTER 1: RESEARCH BACKGROUND AND PURPOSE OF THE STUDY	
1.1 Research background of energy resource	1-1
1.1.1 Current status and bottleneck of international energy development	1-1
1.1.2 The significance of developing variable renewable energy	1-4
1.2 Development status of renewable energy	1-8
1.2.1 The development and status of renewable energy in the world	1-8
1.2.2 The development and status of renewable energy in Japan.....	1-17
1.3 Research structure and logical framework	1-25
1.3.1 Research purpose and core content	1-25
1.3.2 Chapter content overview and related instructions	1-26
Reference	1-30
 CHAPTER 2: LITERATURE REVIEW OF RENEWABLE ENERGY SYSTEM	
2.1 Development of renewable energy in the power systems	2-1
2.1.1 Variable renewable energy (VRE) studies.....	2-1
2.1.2 Pumped storage systems (PHS) studies	2-10
2.2 Evaluation indicators of the impact of renewable energy on the power grid	2-12
2.3 EnergyPLAN models	2-15
Reference	2-17

CHAPTER 3: METHODOLOGY

3.1 Evaluation indicators of VRE on the power grid	3-1
3.1.1 Capacity credit analysis.....	3-1
3.1.2 Evaluation indicators of VRE integration	3-5
3.2 Prediction of PHS installed capacity	3-7
3.2.1 The geographical position required of PHS constructions	3-7
3.2.2 The efficiency calculation of PHS power generation.....	3-9
3.2.3 The prediction of PHS in this paper	3-10
3.3 EnergyPLAN model analysis	3-13
3.3.1 The basic introduction about EnergyPLAN model	3-13
3.3.2 Finding and inputting data into EnergyPLAN	3-15
3.3.3 The utilization of EnergyPLAN model with PHS facilities	3-21
Reference.....	3-24

CHAPTER 4: DATA RESOURCES AND ENERGY CONVERSION ANALYSIS

4.1 Content.....	4-1
4.2 Data resources	4-1
4.2.1 Distribution of research area	4-1
4.2.2 Comparison of the power generation composition.....	4-11
4.2.3 Load profiles and VRE generation profiles.....	4-12
4.2.4 Economic cost of power generators	4-20
4.3 Energy conversion analysis	4-21
4.4 The operation strategies of different power generation unit.....	4-27

Reference	4-30
------------------------	------

CHAPTER 5: ASSESSMENT OF RENEWABLE ENERGY INTEGRATION IN SUPPLY SIDE

5.1 Contents	5-1
5.2. Results and analysis	5-3
5.2.1 Results and analysis of RLDCs.....	5-4
5.2.2 Results and analysis of capacity credits	5-7
5.2.3 Results and analysis of DIPP	5-9
5.3. Conclusions and future research	5-12
5.3.1 Conclusions.....	5-12
5.3.2 Limitations and future research.....	5-13
Reference	5-14
Appendix	5-14

CHAPTER 6: ASSESSMENT OF DEMAND SIDE LOAD IN VRE INTEGRATION

6.1 Contents	6-1
6.2 Background and research objective	6-1
6.2.1 Background.....	6-1
6.2.2 Research objective	6-4
6.2.3 Data sources	6-6
6.3 Methodology and constraints	6-7
6.3.1 Electricity load balance between supply and demand.....	6-7
6.3.2 Impact of power generators on electricity price.....	6-8
6.4 Electricity consumptions change during the COVID-19 pandemic	6-8

6.4.1 Total load demand reduction	6-8
6.4.2 Dispatch on power generation sectors.....	6-10
6.5 Changes in load profiles and their impact on renewable energy sources.....	6-11
6.5.1 Load-related statistics.....	6-11
6.5.2 Impact on PV integration	6-20
6.5.3 Impact on electricity price.....	6-23
6.6 Discussion and Conclusions.....	6-24
Reference.....	6-26
Appendix.....	6-31

CHAPTER 7: ECONOMIC AND POTENTIAL ANALYSIS OF RENEWABLE ENERGY HYBRID WITH PUMPED STORAGE SYSTEM

7.1. Research contents.....	7-1
7.2. Accuracy of the EnergyPLAN model of Japan power grid	7-2
7.2.1. Background.....	7-2
7.2.2. Data resource for the verify of EnergyPLAN model.....	7-6
7.2.3. Results and analysis on the outputs of EnergyPLAN.....	7-9
7.2.4. Conclusions of the verify results.....	7-11
7.3. Result and analysis of PHS prediction	7-12
7.3.1. Result and analysis of potential PHS installed capacity.....	7-12
7.3.2. CEEP of RES	7-13
7.3.3. Compression on thermal power generation.....	7-17
7.3.4 Cost of power generation	7-19
7.4. Discussion and imitation of the EnergyPLAN model.....	7-20
7.5. Conclusions.....	7-21

7.6. Sensitivity analysis of nuclear power generation.....	7-22
7.6.1. Background.....	7-22
7.6.2. Results and analysis	7-23
7.6.3. Conclusions and limitations of this research.....	7-30
Reference.....	7-31
Appendix.....	7-34

CHAPTER 8: CONCLUSION AND PROSPECT

8.1 Conclusion.....	8-1
8.2 Prospect.....	8-3

CONTENTS OF FIGURES

CHAPTER 1: RESEARCH BACKGROUND AND PURPOSE OF THE STUDY

Fig. 1-1 Trends in global primary energy consumption	1-1
Fig. 1-2 Proportions of the trends in global primary energy consumption.....	1-2
Fig. 1-3 Global greenhouse gas (GHG) emissions and global mean temperature change	1-2
Fig. 1-4 Outlook for world energy demand.....	1-3
Fig. 1-5 CO ₂ emissions from global fossil fuel combustion and industrial processes from 1750 to 2020	1-5
Fig. 1-6 Comparison of primary energy self-sufficiency ratios of major countries (2017)	1-6
Fig. 1-7 Comprehensive energy self-efficiency statistics in Japan	1-6
Fig. 1-8 Trends in the composition of primary energy supply of Japan.....	1-8
Fig. 1-9 Energy and electricity structures of worldwide	1-9
Fig. 1-10 Renewable electricity investment and capacity additions, 2013-2017	1-9
Fig. 1-11 Renewable share by category and country in the new policies scenario, 2017 and 2040	1-10
Fig. 1-12 Global renewables-based electricity support in the new policies scenario.....	1-10
Fig. 1-13 The timeline of renewable energy policy implemented in the United States	1-13
Fig. 1-14 The timeline of renewable energy policy implemented in Germany.....	1-13
Fig. 1-15 The timeline of renewable energy policy implemented in China	1-15
Fig. 1-16 The timeline of renewable energy policy implemented in Japan	1-16
Fig. 1-17 Changes in the Japan composition of power sources (supply) (upper and lower).....	1-17
Fig. 1-18 Changes in average electricity price in residential and industrial aspect.....	1-18
Fig. 1-19 Changes in the installed capacity resulting from renewable energy (except for large scale hydroelectric power)	1-19

Fig. 1-20 Trends in surcharge after introducing FIT scheme	1-19
Fig. 1-21 The history of primary energy consumption sector	1-22
Fig. 1-22 The composition of industrial energy consumption	1-22
Fig. 1-23 The composition of residential energy consumption	1-24
Fig. 1-24 The energy consumption in the passenger sector	1-25
Fig 1-25 Research logic of the article	1-26
Fig 1-26 Chapter name and basic structure.....	1-26
Fig 1-27 Brief chapter introduction.....	1-27

CHAPTER 2: LITERATURE REVIEW OF RENEWABLE ENERGY SYSTEM

Fig. 2-1 Installed PV capacity in Japan on 2017.....	2-2
Fig. 2-2 Maximum and minimum power demands with existing and planned PV capacity in Japan in 2017	2-3
Fig. 2-3 Resource potential of renewable energy in Japan, compiled form (MOE 2011).....	2-4
Fig. 2-4 Annual and cumulative wind energy installation in Japan (2000–2020).....	2-4
Fig. 2-5 Wind energy potentials and existing power generation capacity by Electricity Power Company.....	2-5
Fig. 2-6 Current bottlenecks and risks of onshore wind energy development in Japan.....	2-6
Fig. 2-7 Grid-connected hybrid system at common current converters	2-7
Fig. 2-8 A hybrid solar-wind system with PHS (a) with two penstocks (b) with single penstock	2-12
Fig. 2-9 Capacity credit data by VRE type	2-13
Fig. 2-10 Breakdown of dataset by category of impact	2-14
Fig. 2-11 Geographic scale of EnergyPLAN analyses 2003–2015	2-17
Fig. 2-12 Application of different criteria in the reference that applying in EnergyPLAN model as	

of May 26th, 2015.....	2-17
------------------------	------

CHAPTER 3: METHODOLOGY

Fig. 3-1 Load curve at hourly interval for one-year.....	3-1
Fig. 3-2 LDC is derived by sorting the load curve (Fig. 3-1) in descending order	3-2
Fig. 3-3 VRE power generation profile.....	3-2
Fig. 3-4 RLDC is derived by subtracting the time series of VRE from the time series of power demand (Fig. 3-1).....	3-3
Fig. 3-5 LDC and RLDC.....	3-4
Fig. 3-6 Illustration of capacity credit metric.....	3-5
Fig. 3-7 The existing PHS facilities in Japan	3-7
Fig. 3-8 The configuration of PHS interconnected	3-9
Fig. 3-9 A pure pumped storage power plant with a dish-shaped artificial lake as an upper pond	3-10
Fig. 3-10 The relationship between effective storage of water resource and possible utilized water resource of power generation.....	3-12
Fig. 3-11 Basic layout with main parameters of the PHS with dams.....	3-12
Fig. 3-12 Schematic diagram of the EnergyPLAN tool.....	3-14
Fig. 3-13 The inputted data of electricity demand in EnergyPLAN	3-15
Fig. 3-14 The inputted data of renewable energy in EnergyPLAN.....	3-16
Fig. 3-15 The inputted data of central power plants in EnergyPLAN.....	3-17
Fig. 3-16 The inputted data of electricity storage system and operation strategies in EnergyPLAN	3-17
Fig. 3-17 One PHS facility with (A) a single penstock system and (B) a double penstock system....	3-18
Fig. 3-18 The inputted data of fuel cost in EnergyPLAN	3-19

Fig. 3-19 The inputted data of investment, operation (upper), and fuel cost (bottom) for power generators in EnergyPLAN	3-20
Fig. 3-20 Facility composition of the electricity co-ordination of supply and demand	3-21
Fig. 3-21 Energy management flowchart with the strategies of PHS operation	3-22
Fig. 3-22 Hourly basis on pumped hydro ratio and VRE ratio in Kyushu (upper) and Kansai (bottom) area.....	3-23
Fig. 3-23 Demand and supply balance in Kyushu and Kansai area	3-24

CHAPTER 4: DATA RESOURCES AND ENERGY CONVERSION ANALYSIS

Fig. 4-1 Installed capacity of PV and wind power and its regional distribution for Kyushu, Tokyo, Kansai, and Hokkaido electricity companies	4-2
Fig. 4-2 The progress of the composition of power generations and installed capacity in Kyushu	4-2
Fig. 4-3 The progress of fossil fuel energy consumption and cost.....	4-3
Fig. 4-4 The energy distribution in Kyushu	4-3
Fig. 4-5 The live photo of Sasebo Mega Solar Power Plant (upper), and Nagashima Wind Power Plant (bottom)	4-4
Fig. 4-6 The PV power generation profiles in terms of me meteorological conditions, which is located in Sasebo Mega Solar Power Plant.....	4-5
Fig. 4-7 The wind power generation profiles in terms of me meteorological conditions, which is located in Nagashima Wind Power Plant	4-6
Fig 4-8 Energy distribution in Hokkaido	4-7
Fig. 4-9 The progress of variable power generation shares in Hokkaido power grid	4-7
Fig. 4-10 The total power generation by energy resource in Kansai power grid	4-8
Fig. 4-11 The thermal efficiency of thermal power plant in Kansai power grid	4-9
Fig. 4-12 Energy distribution in Tokyo	4-9

Fig. 4-13 The progress of power generation proportions by different energy types in Tokyo power grid.....	4-10
Fig. 4-14 The thermal efficiency of thermal power plant in Tokyo power grid.....	4-10
Fig. 4-15 Configuration of power generation in Kyushu, Tokyo, Kansai, and Hokkaido (in 2019)	4-11
Fig. 4-16 Load profiles in Kyushu power grid.....	4-12
Fig. 4-17 Load profiles in Tokyo power grid	4-12
Fig. 4-18 Load profiles in Hokkaido power grid	4-13
Fig. 4-19 Monthly-averaged hourly data of load profile over one-year in Kyushu and Hokkaido	4-13
Fig. 4-20 The Monthly-averaged daily net power production from PV module and wind turbine in Kyushu, Hokkaido, Tokyo, and Kansai power grid, respectively	4-15
Fig. 4-21 Hourly residual load for days of different months with PV or wind production to grid load ratios of 0%-30% for Kyushu and Hokkaido	4-16
Fig. 4-22 Load duration curve with one daily data in Kyushu and Hokkaido	4-20
Fig. 4-23 Flowchart of thermal electricity generation.....	4-28
Fig. 4-24 Electricity consumption shares at demand side in Kyushu, Tokyo, Kansai, and Hokkaido	4-21
Fig. 4-25 Prediction of thermal power capacities in Kyushu and Hokkaido until 2040. (Mistake of legend, order of LNG and Oil).....	4-21
Fig. 4-26 Kyushu power system operations November 4, 2018	4-22
Fig. 4-27 Simplified presentation of curtailment rule of power plants in Japan	4-23
Fig. 4-28 The daily operation of different power generators hybrid PHS and battery facilities .	4-24

CHAPTER 5: ASSESSMENT OF RENEWABLE ENERGY INTEGRATION IN SUPPLY SIDE

Fig. 5-1 The distribution of research area in Japan	5-3
---	-----

Fig. 5-2 Research framework.....	5-3
Fig. 5-3 RLDCs of PV and wind production to grid load ratios 0%-30% for Kyushu, Tokyo, Kansai, and Hokkaido	5-5
Fig. 5-4 The PV into grid with the PV power generation shares increasing.....	5-6
Fig. 5-5 The wind into grid with the wind power generation shares increasing.....	5-6
Fig. 5-6 The monthly curtailment distribution of PV power generation in Hokkaido	5-7
Fig. 5-7 The monthly curtailment distribution of PV power generation in Hokkaido	5-7
Fig. 5-8 Graphical illustration of PV power capacity credit calculation process	5-8
Fig. 5-9 Relationship between capacity credit and ratio of PV power production for Kyushu and Tokyo, and wind power production for Kansai and Hokkaido	5-8
Fig. 5-10 Effective hours of PV power generation in Kyushu and Tokyo, and wind power generation in Kansai and Hokkaido, respectively.....	5-11
Fig. 5-11 DIPP of PV and wind and its overproduction rate in Tokyo, Kansai, and Hokkaido ...	5-11

CHAPTER 6: ASSESSMENT OF DEMAND SIDE LOAD IN VRE INTEGRATION

Fig. 6-1 Research framework.....	6-5
Fig. 6-2 Distribution of infected people and research areas (as of May 31, 2020)	6-5
Fig. 6-3 Composition of power generation sectors in research areas (2019).....	6-6
Fig. 6-4 Comparison of demand reduction for the month of April and May 2019 and 2020 for Kyushu, Tokyo, Kansai, and Hokkaido.....	6-9
Fig. 6-5 Breakdown of power generation for April and May 2019 and 2020 for Kyushu, Tokyo, Kansai, and Hokkaido	6-10
Fig. 6-6 Comparison of load histograms for April and May 2019 and 2020 for Kyushu, Tokyo, Kansai	6-12
Fig. 6-7 Comparison of weekly load profiles for April and May 2019 and 2020 for Kyushu, Tokyo, Kansai, and Hokkaido	6-13

Fig. 6-8 The comparison of load changes in 2020 compared with previous years under the same temperature in Kyushu.....	6-16
Fig. 6-9 The comparison of load changes in 2020 compared with previous years under the same temperature in Tokyo	6-16
Fig. 6-10 The comparison of load changes in 2020 compared with previous years under the same temperature in Kansai	6-18
Fig. 6-11 The comparison of load changes in 2020 compared with previous years under the same temperature in Hokkaido.....	6-19
Fig. 6-12 PV penetration histograms for April and May 2019 and 2020 for Kyushu, Tokyo, Kansai, and Hokkaido.....	6-21
Fig. 6-13 Comparison of daily power balance for April and May 2019 and 2020 in Kyushu and Tokyo	6-22
Fig. 6-14 Market spot trading prices in Kyushu during April and May 2019 (left) and April and May 2020 (right).....	6-23
Fig. 6-15 Histogram of spot market prices in Kyushu, Tokyo, Kansai, and Hokkaido during April and May 2019 (left) and April and May 2020 (right)	6-24

CHAPTER 7: ECONOMIC AND POTENTIAL ANALYSIS OF RENEWABLE ENERGY HYBRID WITH PUMPED STORAGE SYSTEM

Fig. 7-1 Research flow	7-2
Fig. 7-2 Research framework.....	7-4
Fig. 7-3 The basic configuration of EnergyPLAN model.....	7-6
Fig. 7-4 The location scenario in Kyushu region.....	7-6
Fig. 7-5 The capacity structure of Kyushu power grid in 2018.....	7-7
Fig. 7-6 Load profile of Kyushu electric power.....	7-7
Fig. 7-7 The PV power generation in Kyushu.....	7-8
Fig. 7-8 The wind power generation in Kyushu in 2018.....	7-9

Fig. 7-9 Daily balance of power generation.....	7-9
Fig. 7-10 Power generated of PHS in EnergyPLAN model.....	7-11
Fig. 7-11 Comparison of current and potential PHS power generation capacity in different electricity power companies	7-13
Fig. 7-12 CEEP of PV, wind, and RES in Kyushu and Hokkaido (database: 2019, PHS=0).....	7-14
Fig. 7-13 Proportion of power generation mix under variable scenarios in Hokkaido	7-14
Fig. 7-14 Proportion of power generation mix under variable scenarios in Kyushu.....	7-16
Fig. 7-15 RES output integrated into the Kyushu and Hokkaido grid	7-16
Fig. 7-16 The surplus electricity of VRE production in Kyushu.....	7-17
Fig. 7-17 Operation of thermal power plant in monthly interval on Hokkaido power grid	7-18
Fig. 7-18 The composition of different power generators in March and August of Kyushu.....	7-19
Fig. 7-19 Average cost of power generation profiles with RES proportion changes in Kyushu and Hokkaido.....	7-20
Fig. 7-20 Simplified presentation of curtailment rule of power plants in Japan	7-24
Fig. 7-21 The comparison of electricity generation with or without nuclear power generation in Kyushu area	7-27
Fig. 7-22 The comparison of electricity curtailment of VRE with or without nuclear power generation in Kyushu area.....	7-28
Fig. 7-23 The comparison of VRE into grid of VRE with or without nuclear power generation in Kyushu area	7-28
Fig. 7-24 The comparison of electricity load with or without nuclear power generation in Kyushu area.....	7-29
Fig. 7-25 The comparison of thermal power generation with or without nuclear power generation in Kyushu area	7-29
Fig. 7-26 The comparison of PHS power generation with or without nuclear power generation in Kyushu area	7-30
Fig. 7-27 The configuration of electricity generation under the circumstance of PHS and nuclear power facilities.....	7-32

CHAPTER 8: CONCLUSION AND PROSPECT

Fig. 8-1 The fourth fold of paper analysis..... 8-3

CONTENTS OF TABLES

CHAPTER 1: RESEARCH BACKGROUND AND PURPOSE OF THE STUDY

Table 1-1 Japan's dependency on imports from overseas for fossil fuel resources.....	1-8
--	-----

CHAPTER 2: LITERATURE REVIEW OF RENEWABLE ENERGY SYSTEM

Table 2-1 Type of each tool reviewed.....	2-15
---	------

CHAPTER 3: METHODOLOGY

Table 3-1 Related parameters of DIPP.....	3-7
---	-----

Table 3-2 Design requirements of new PHS Power Station.....	3-11
---	------

CHAPTER 4: DATA RESOURCES AND ENERGY CONVERSION ANALYSIS

Table 4-1 The summarized amount of electricity power generation.....	4-8
--	-----

Table 4-2 Summarized data of VRE in different power grid	4-11
--	------

Table 4-3 Summarized of cost assumption	4-28
---	------

Table 4-4 Current installed capacity and penetration in four areas, as for 2019	4-19
---	------

Table 4-5 Predicted ratios of PV and wind energy under different years.....	4-19
---	------

Table 4-6 Descriptive summarized of thermal power plant in Hokkaido	4-20
---	------

CHAPTER 5: ASSESSMENT OF RENEWABLE ENERGY INTEGRATION IN SUPPLY SIDE

Table 5-1 DIPP and overproduction rate of PV in Kyushu	5-12
--	------

Table 5-2 Calculated maximum PV and wind penetration and its corresponding parameters 5-13

CHAPTER 6: ASSESSMENT OF DEMAND SIDE LOAD IN VRE INTEGRATION

Table 6-1 Descriptive statistics for PV power generation in 2019 and 2020 (April to May)..... 6-20

Nomenclature

Label	Unit	Description
IEA	-	International energy agency
LNG	-	Liquefied natural gas
GDP	-	Gross domestic product
RPS	-	Renewable portfolio standard
ITC	-	Investment tax credit
PTC	-	Production tax credit
FiT	-	Feed-in tariff
FIP	-	Feed-in premium
DIPP	-	Dynamic investment payback period
VRE	-	Variable renewable energy
PHS	-	Pump storage system
FY	-	Fiscal year
RPS	-	Renewable Portfolio Standard
EIA	-	National Environmental Impact Assessment
LCOE	-	Levelized cost of energy or electricity
RLDC	-	Residual load duration curves
LDC	-	Load duration curve
CRL	-	Cumulative residual load
PtG	-	Electricity-to-gas
PES	-	Primary energy supply
PV	-	Photovoltaic
DSM	-	Demand-side management
MGSS	-	Minimum grid stability share

Label	Unit	Description
MGSPS	-	Minimum grid stabilization production share
CEEP	-	Critical Excess Electricity Production
RE	-	Renewable energy
JHU	-	Johns Hopkins University
UHV	-	Ultra-high voltage
PRC	-	Polynomial regression curve
X	-	Guaranteed load reduction without PV integration
Y	-	Guaranteed load reduction with PV integration
P	Yen/kWh	Electricity price
P_b^t	MWh	Power flow from base-load plants
P_m^t	MWh	Power flow from flexible plants
VRE_{direct}	MWh	Directly integrated VRE power generation
$load_{grid}^t$	MWh	Total grid load
P_{VRE}^t	MWh	Total VRE production
overproduction(t)	MWh	Curtailed VRE production
T2	h	Starting hours of excess electricity
T1	h	Finishing hours of excess electricity
RLDC(t)	MWh	Residual load demand
P_t	Year	Dynamic investment payback period of PV or wind
i_t	%	Annual interest rate
t	h	Time unites
C_0	Yen/kWh	Initial investment
C_1	Yen/kWh	Annual revenue
η	%	Total efficiency of PHS power generation

Label	Unit	Description
η_{TG}	%	Efficiency of turbine generator
η_{TP}	%	Efficiency of pumping facility
V_0	10^3m^3	Effective water storage capacity
V_1	10^3m^3	Potential pumped storage
H	M	Head conditions
S	MW	Capacity of installed capacity
P	MWh	Capacity of power generation
P_y	MWh/y	Total power generation for a year
$PHS_{storage}$	kWh	Storage capacity of electricity power
V	m^3	Volume of upper reservoir,
g	m/s^2	Gravitational acceleration
h	m	Head between upper and lower reservoir
C	kW	Rated power generation
η	%	Overall efficiency
E_{out}	MWh	Total electricity produced from the research objective
E_{in}	MWh	Total electricity consumed
e_{stab}	MWh	Total electricity production from grid stabilizing units
d_{stab}	%	Minimum grid stabilization production share
i	h	Time unit
$dispatch^i$	MWh	Flexible thermal power generators
$discharge^i$	MWh	The amount of electricity pumped by PHS
$charge^i$	kWh	The amount of electricity generating by PHS

Label	Unit	Description
η_{pump}	%	Water pump efficiency
$\eta_{turbine}$	%	Turbine efficiency
C_{pump}	MW	Maximum capacity of pump
$C_{turbine}$	MW	Maximum capacity of turbine
$supply^i$	MWh	Total electricity generation by all power sectors
$nuclear^i$	MWh	Power generated by nuclear energy
RES^i	MWh	Power generated by RES energy
ρ	kg/m ³	Density
$Price$	Yen	Average price of fuel at per unit
LHV	MJ/kg	Lower heating value of coal, oil, and LNG
θ	%	Efficiency of thermal power plant electricity generation
P_{cons}	MWh	Power generation from base-load plants
P_{flex}	MWh	Flexible generators that can adjust their output to adapt to the situation of the PV and power grid
PV_{direct}	MWh	Directly accommodated PV
$Load_{direct}$	MWh	Total electricity demand
P_{PV}	MWh	Total PV power generation
$output$	MWh	Total electricity generation on the supply side
$trans$	MWh	Flow of power transferred across regional transmission lines