Estimating Values of Integrated PV-Battery Systems for Single-Detached Residences in Japan

by

Mutsumi Sato

A thesis

presented to the University of Waterloo

in fulfillment of the

thesis requirement for the degree of

Master of Environmental Studies

in

Sustainability Management

Waterloo, Ontario, Canada, 2017

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Climate change is now widely acknowledged as a threat facing the current generation. To combat this, photovoltaic (PV) power generation, one of the renewable energy sources, has been regarded as a preferable solution to meet the growing energy demands by producing electricity cleanly and sustainably. The utilization of PV has developed at a significant speed at a global scale. Amongst the different types of PV power generation, utilizing it with a combination of battery storage systems, integrated PV-battery systems, at the residential level, are attracting increased attention today worldwide, including Japan. It is believed that the systems will contribute to changing how electricity is produced and consumed, which is a fundamental change to mitigate climate change.

However, while the cost of PV systems has decreased over the years, the high cost of batteries causes consumers to hesitate to install PV-battery systems at their homes. This thesis explores the economic return on residential integrated PV- plus lithium ion battery systems in Japan. Using twelve and twenty-four month actual electricity consumption data (12 and 24 month duration to cover all seasons) from single detached houses in Kyoto, Japan, along with data from Japanese government sources and past literature, this study evaluates the expected financial returns of integrated PV-battery systems under 36 scenarios. The primary financial indicators used in this study are Net Present Value (NPV) and Internal Rate of Return (IRR).

The results indicated that most of the scenarios did not create positive economic returns. For scenarios which showed negative results, sensitivity analysis was conducted to estimate a break-even cost of battery, as the high cost associated with the installation of the integrated PV-battery systems is one of the main obstacles for wide use of this technology. The results indicated that for the systems to show NPV=0, the cost of batteries needs to decrease substantially.

This study provides new knowledge on residential integrated PV-lithium-ion battery systems in the context of the Japanese residential sector, which has not been explored in past literature. This research also holds valuable information for policy makers and associated businesses to enhance the development and use of the systems in the Japanese residential sector.

Keywords: PV-Battery Systems; Residential Energy Scenarios; Net Present Value; Internal Rate of Return; Japan

Acknowledgements

I would like to express my sincere gratitude to Dr. Paul Parker, my supervisor, for generous guidance and input to make my thesis at this stage. My acknowledgement also extends to Dr. Michael Wood and Dr. Mark Seasons.

I would like to also thank my wife for her support. Your presence was the greatest asset that I had not only throughout my thesis writing, but also throughout my time spent abroad pursuing a master's program.

To my parents, sister, grandmother, and my late grandfather, thank you for giving me your unconditional love and for being available to listen when I needed most. I am so proud of having you as my family. Without you all, I could not have become the person that I am today.

To my friends in the program of Sustainability Management, it has been my privilege getting to know you. I have gained a lot of knowledge learning from you. I hope our bond of friendship lasts forever.

Lastly, my sincere gratitude goes to people who made this thesis research all possible, who provided me with access to the electricity load profile data and the economics information, and to energy and environment experts in an international organization for sharing your generous knowledge with me.

Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction

1.1 Background

Energy is one of the fundamental needs for activities of daily living. However, the world is faced with a fundamental threat to our lives, climate change, and energy use is the major contributing factor to climate change. The energy sector accounts for nearly 60% of global greenhouse gas (GHG) emissions (Sustainable Energy for All, n.d.). As a way to address this issue and other social and environmental problems, renewable energy technologies have been receiving increased attention (Hoppmann, Volland, Schmidt, & Hoffmann, 2014; Liu, Rasul, Amanullah, & Khan, 2012). The agreement adopted at the 21st Annual Conference of Parties (COP21) in Paris, France, and Goal 7 in the Sustainable Development Goals (SDGs) emphasize the importance of the use of clean energy including renewable energy for sustainable development.

In 2014, the share of renewable energy sources in the global energy supply mix reached 18.4% (IRENA, 2016). The International Renewable Energy Agency (IRENA) proposed a roadmap to double the total share of renewable energy supply to 36% by 2030 (IRENA, 2016). Amongst many types of renewable energy technologies, Photovoltaic (PV) generation has been recognized as one of the most common methods to generate electricity cleanly and sustainably based on its low price, easy installation and management requirements compared to other renewable energy sources (Huang & Wu, 2007). Nearly 50 GW of PV was installed in the grid globally in 2015 (IEA PVPS, 2016). Between 2010 and 2015, PV generation increased at an average annual growth rate of 42% (Renewable Energy Policy Network for the 21st Century, 2016).

In recent years, Japan has been increasing the use of renewable energy sources, especially PV generation, in its total energy mix. Since 2012, the use of electricity from PV generation has been growing substantially, which ranked the country as the fourth largest solar PV market in the world (REN 21, 2016).

PV technology can provide electricity from small scale, mainly for use at the residential level, to large scale, for use at the commercial level. The use of small-scale generation has increased rapidly, mainly for household purposes. In 2013, about 25% to 35% of global cumulative PV capacity was recorded from the residential sector (IEA-RETD, 2014). An introduction of new government policies, such as the Feed-in Tariff (FIT) program, and increased awareness towards clean energy and environment from the public stimulated the significant increase in use of PV generation at the residential level.

With the increase in the use of PV systems at the household scale, the use of battery storage systems together with the PV systems has also gained attention. As of November 2016, more than 75,000 households in Japan have installed integrated PV-battery storage systems (Agency for Natural Resources and Energy, 2014). Integrated PV-battery storage systems can bring benefits to consumers, such as providing a backup power system and reducing electricity bills by using time-of-use

(TOU) billing management (Cole, Marcy, Krishnan, & Margolis, 2016; Fitzgerald, Mandel, Morris, & Touati, 2015). As a way to assess the net benefits of installing PV-battery storage systems at the household scale, this thesis studies the economic implications of use of PV plus lithium ion battery systems in the residential sector in Japan.

1.2 Problem statement

Integrated PV-battery systems at the residential level allow homeowners to increase the rate of PV self-consumption and to achieve greater energy security by increasing the consumption of electricity generated on site (Fitzgerald, Mandel, Morris, & Touati, 2015). It also contributes to lower electricity costs by effectively using TOU bill management: one can charge energy using the storage systems during off-peak pricing period and use the stored energy during on-peak pricing periods to avoid using expensive electricity (Cole et al., 2016; Kousksou, Bruel, Jamil, El Rhafiki, & Zeraouli, 2014; International Electrotechnical Commission, 2011).

While the literature explores the positive relationship between PV and battery storage systems for sustainable energy use, the installation of small-scale battery storage systems has progressed at a slow rate. The benefits of installing the storage system have not been convincing enough to most residents to install the system for energy use. The report, “Renewables and Electricity Storage” by IRENA, concludes that cost is one of the reasons that the storage system has been constrained in the market (2015). Unlike FIT programs and other subsidies for the PV solar system, which allow consumers to easily identify economic benefits of the system, limited information and high costs of the residential battery storage system have prevented users from purchasing the system. As presented by Kantor et al., there has to be a clear indication of net economic benefits for households to install the system (2014).

1.3 The significance of the problem and contributions of the study

Through past literature, it can be found that scholars have conducted studies on various aspects of integrated PV-battery systems, such as technology, financial performance, and the optimization of the systems. From the current literature, three major limitations can be noted. The first issue is the type of battery that past academic scholars have reviewed. Many of the researches used lead-acid batteries as the battery storage studied because of their availability and lower costs. However, lithium ion batteries offer a preferable option to be used for future battery storage systems because of their improved performance and declining costs (Darcovich et al., 2013; Scrosati & Garche, 2010). Large investments have been made to study and develop lithium-ion batteries, resulting in lower production cost, placing them as one of the most viable options for use in battery storage systems (Nair & Garimella, 2010). As Brunch and Muller (2014) note, conducting the profitability analysis of PV-lithium-ion battery systems is an interesting field area to study. Therefore, this study uses lithium-ion batteries as a preferred battery storage system to be studied.

The second issue is the geographic areas of study. Many of the studies on integrated PV-battery systems for use in the residential sector can be found in Europe, as it is one of the regions in the world where there are many initiatives to integrate various renewable energy sources into the electrical system. On the other hand, literature on the potential economic benefits of using a small-scale battery storage system in households with PV panels in Japan are limited, regardless of the recent progress and achievements Japan has made in this area. Yoza et al. (2014) assessed the monetary benefits of integrated PV-battery systems in the Japanese residential sector. However, this study also falls short, as it does not mention the type of battery used. Thus, conducting a study on PV-lithium ion battery systems in Japan can make a positive contribution to this research area.

The third issue is language. Many of the academic literates written by Japanese scholars are in Japanese; thus it limits the accessibility and value that can be offered to scholars outside of Japan. Dissemination of research results in English allows the sharing of findings with worldwide scholars on the advancement Japan has made to date.

This thesis, will contribute new findings to the international literature by assessing the economic viability of integrated PV-plus-lithium ion battery systems in Japan. Moreover, this study uses actual electricity consumption data that offers an accurate and practical economical evaluation on integrated PV-battery systems.

1.4 Thesis objective and questions

The ultimate objective of this study is to identify factors that influence the adoption rates of integrated PV-battery systems in the Japanese residential sector. One of the major factors associated with the use of integrated PV-battery systems at households is cost. Therefore, this research focuses on the financial performance of integrated PV-battery storage systems; and aims to answer the following questions:

1. *Under what conditions will PV + battery storage systems create positive economic returns?*
2. *Are economic incentives necessary for PV + battery storage systems to be profitable?*

1.5 Thesis methodology

This thesis aims to identify the economic profitability of integrated PV-plus-battery storage systems by using actual electricity consumption data from two houses in Kyoto, Japan. The study uses the database from New Energy and Industrial Technology Development Organization (NEDO) to calculate the potential energy output from solar PV. The PV-battery systems related to size, costs and technical battery performances are determined based on available data. The study uses the Net Present Value (NPV) and the Internal Rate of Return (IRR) as economic indicators to assess if estimated costs will create economic benefits for the two houses to install the systems at their homes. In addition, sensitivity analysis is performed on the input variable, cost of battery, to assess its effect on the overall performance.

1.6 Worldview

This study takes a quantitative approach with the positivist worldview. The study is conducted based on an assumption that in order to justify the use of a small-scale battery system, (i) NPV calculation on integrated PV-plus-battery systems should be greater than 0, and (ii) IRR value of integrated PV-plus-battery systems should indicate a high number to justify an investment. The results of NPV calculation greater than 0, and higher IRR demonstrate that they provide economic incentives to users, justifying the installation of the system in homes. The positivist worldview focuses on verifying a theory through detailed observation of measurable facts. Based on the positivist's view, this study tests the hypothesis with quantitative data (Willis and Jost, 2007).

1.7 Thesis structure

This thesis is comprised of six chapters. The first chapter provides introductory information. The second chapter summarizes current literature reviewed, followed by general overview of the study in the following chapter. The fourth chapter discusses the methodology, and data collection process of the study. The fifth chapter reports the results of statistical analysis and key findings. The thesis concludes by presenting a summary and comments for future studies.

Chapter 2: Literature Review

2.1 Introduction

Residential PV-battery systems offer alternatives to a traditional electricity supply scheme, in which households depend on electricity grids for their electricity supply. As the issue of climate change increases in importance, integrated PV-battery systems are regarded as one of the potential solutions to mitigate environmental impacts, receiving increased attention from scholars.

Various studies have been conducted in the field of integrated PV-battery systems to assess their potential use in households. It has been proven technologically from many studies including scholars and non-scholars that integrated PV-battery systems can provide advantages to the users. According to Fitzgerald et al. (2015), battery storage systems can offer four services and values to consumers: (1) backup power; (2) increase the rate of PV self-consumption; (3) reduce demand charges; and (4) TOU bill management.

The economic values of integrated PV-battery systems for residents, however, are not as clear as their technological benefits. While technological advantages of the systems can be assessed under a common benchmark, the economic viability of the integrated PV-battery systems depend on a wide range of criteria, such as interest rate, inflation or deflation rate, the cost of PV-battery systems that depend on the size of PV and battery capacity, which make the systems difficult to be assessed (Bruch & Müller, 2014).

According to the survey by Graebig et al. (2014), 80% of survey respondents in Germany showed interest in installing integrated PV-battery systems in their homes to save on their electricity bills. Moreover, 69% of respondents are interested to have PV-battery systems installed to be self-sufficient (Graebig, Erdmann, & Röder, 2014). However, their study showed that interviewers' willingness to install the systems do not match with the realistic pay-back of the systems. The study found that the biggest motivation for households to install the systems is to be self-sufficient and not based on monetary benefits (Bruch & Müller, 2014; Graebig et al., 2014). As a result, it could be expected that some customers would invest in the systems with less attention on costs because the perceived benefits of being independent outweigh the economic costs (Weniger, J., Bergner, J., Tjaden, T., & Quaschning, 2014). Brunch & Müller (2014) claimed that investment on the PV-battery storage systems should not create financial burdens for consumers; therefore, detailed economic analyses of the systems that incorporate regional contexts are recommended.

2.2 Worldwide study on PV-battery systems

A number of academic studies have been conducted in the field of integrated PV-battery systems. Various aspects of the systems have been studied such as technology aspects, financial performances, and the optimization of the systems. Integrated PV-battery systems have been studied for over a quarter century. For example, Gordon (1987) examined the potential of installing local PV-battery systems in remote and isolated areas in developing countries as an alternative solution to bringing power from a long-distance transmission line or generating electricity from a diesel generating system. His study concluded that integrated PV-battery systems could be a cost-effective solution in developing countries even considering the high system cost.

Research on the optimal sizing of integrated PV-battery systems has been conducted in many regions. Askari and America (2009) studied optimal numbers of PV modules and autonomy hours for battery of off-grid integrated PV-battery systems for remote electrification areas in Kerman, Iran. They used the concept of loss of power supply profitability (LPSP) and levelized cost of energy (LCOE) to find the most optimal configuration of PV-battery systems at minimum costs. The study articulated the importance of setting required system reliability level of PV-battery systems to prevent increase in the cost of the systems. While it is preferred to have a system with less LPSP, because it means the system is more reliable, LCOE of the system increases as the LPSP decreases. Therefore, to avoid expensive investments on PV-battery systems, detailed verification on system reliability level of the systems is recommended.

Mudler et al. (2010) studied the technological aspects of grid-connected residential PV-battery systems. They pointed out important technical elements to determine optimal battery size for PV-battery systems: (1) efficiency; (2) voltage limitation; (3) life cycles; and (4) calendar life. Among them, life cycles and calendar life have a large influence to determine the economic viability of selected batteries. In fact, they are the most challenging factors to accurately assess the cost effectiveness of a battery used for PV-battery systems, because depending on how frequently the battery is charged and discharged as well as the climate condition of where the system is installed, battery life may be shorter than what manufacturers indicate in their performance catalogues.

The study also articulated that batteries for grid-connected residential PV-battery systems tend to have a smaller capacity than the batteries used for off-grid systems. In the case of grid-connected PV-battery systems, it is not effective to install a large capacity of batteries without increasing the capacity of PV system, because PV is the main contributor to be less dependent on the grid and batteries are used to optimize the rate of self-sufficiency.

A number of academic studies have been conducted on the economic evaluations of small-scale PV generation and battery storage systems mainly targeted for the residential sector. Table 1 summarizes the previous studies which focused on the economic implications of integrated PV-battery systems and key parameters that influenced the outcomes in each study.

Table 1: List of studies that investigated the monetary benefits of residential PV-battery systems

Authors	Study location	Study objective	Key variables
Lazou and Papatsoris (2000)	Europe and Mediterranean areas	Economic feasibility of stand-alone PV-battery systems and hybrid PV-battery systems	• Cost of PV panels and auxiliary equipment • Fine system on the use of non-clean energy technologies
Liu et al.	Australia	Economic	• FIT

(2012)		performance of PV-battery systems	
Colmenar-Santos et al. (2012)	Spain	Economic profitability of PV system and PV-battery systems	• Policy framework • Surplus power from PV-battery systems • Access to wholesale market • PV-battery systems cost
Braun et al. (2009)	France and Germany	Economic profitability of PV systems and PV-battery systems	• Battery cost • Electricity cost
Weniger et al. (2014)	Germany	Optimal sizing of integrated PV-battery systems	• Electricity cost • FIT • Investment cost of PV-battery systems
Weniger et al. (2014)	Germany	Break-even point of integrated PV-battery systems	• Interest rate • PV-battery systems cost • Electricity cost • FIT
Naumann et al. (2014)	Germany	Battery cost analysis for the residential PV-battery systems	• Electricity price • Battery cost
Bruch and Muller (2014)	Germany	Cost effectiveness of PV-battery systems	• Battery cost
Graebig et al. (2014)	Germany	Economic profitability of PV-battery systems	• Electricity cost • Battery cost • FIT • Policy support
Hoppman et al. (2014)	Germany	Economic profitability of PV-battery systems	• Wholesale price • Retail price
Cucchiella et al. (2016)	Italy	Economic profitability of PV-battery systems	• PV & battery size • PV-battery cost • Electricity cost • Tax deductions • Insolation level • Self-consumption rate • Battery life

Lazou and Papatsoris (2000) focused on the cost effectiveness of integrated PV-battery systems in the residential sector. They analyzed the economic feasibility of stand-alone PV-battery systems and hybrid PV-battery systems equipped with a back-up generator, for residents in Europe and Mediterranean areas. They calculated LCOE of both systems in 1998 and 2005 and compared both results with the cost of conventional fossil fuel based electricity. Their research concluded that due to a high system cost, LEOC of both systems in 1998 were more expensive than conventional energy sources. However, in 2005 both systems would be able to economically justify their investments to meet the electricity demand of houses in the study areas if (1) the cost of PV panels and auxiliary equipment decrease; and/or (2) if a policy which imposes a fine on the use of fossil fuel based power generation is introduced.

Studies by Liu et al. (2012) and Colmenar-Santos et al. (2012) effectively incorporated policy incentives, such as feed-in-tariff (FIT) scheme, in their research to calculate the total financial performance, which can be regarded as an epoch-making study. Liu et al. (2012) conducted a study on the techno-economic assessment of integrated PV-battery systems to identify an optimal PV size for PV-battery systems in Queensland, Australia. They picked seven places from four different climate zones, and compared the results each other. Their study focused on the impact of the cost of PV system to the overall profitability of PV-battery systems. From their analysis, it was derived that 6 kW PV system could reduce the cost of electricity bills by more than 50% for all the residents in seven areas in Queensland.

Moreover, a larger PV capacity requires higher investment levels, but that would also generate a larger financial return as it enables the owner to sell a larger amount of electricity to the grid at a premium FIT price.

Colmenar-Santos et al. (2012) compared the financial impacts of PV-battery systems with PV systems without batteries in Spain. They found that investing in PV-battery systems was not a profitable option, as they showed a lower IRR than PV systems without batteries. The study presented four key elements to make PV-battery systems economically profitable:(1) the need for a financial incentive framework such as FIT; (2) the price of FIT; (3) investment costs of PV-battery systems; and (4) access to wholesale market. The study addressed the need of a financial incentive mechanism such as FIT to make PV-battery systems a cost-effective option. Also, the price of surplus electricity should be set lower than the current FIT price, 0.331 €/kWh, to increase the rate of self-consumption. As PV cost was one of the dominant costs in overall investment costs, the study confirmed that decreases in the PV investment costs could contribute to an increase in IRR. However, the study does not calculate the impact of the other dominant cost, battery costs, to the overall IRR. Lastly, integrated PV-battery systems present opportunities to increase their financial returns, if energy in a battery storage has access to sell to the wholesale market when there is a high demand; a high demand means that the electricity is traded at higher prices.

While the above literature either focused on lead-acid batteries or lacked in identifying specific type of battery assessed, Braun et al. (2009), Weniger et al. (2014), Weniger et al. (2014), Naumann et al. (2015) Graebig et al. (2014), and Bruch and Muller (2014) studied integrated PV-battery systems, specifically focusing on a lithium-ion battery. Braun et al. (2009) studied a French-German project, Sol-ion, which developed a storage system using lithium ion batteries for residents to increase economic output from PV generation by increasing the rate of self-consumption. Unlike Liu et al. (2012), the study focused on the impact of the cost of batteries to overall economic performance of PV-battery systems. They estimated the monetary benefits of using the Sol-ion system by comparing additional incomes that could be expected from using the systems against additional costs to install the system. Their study found that if the cost of battery decreases to 350 €/kWh or lower, Sol-ion system could be profitable between the 15th and 20th year of an investment. Moreover, the study confirmed that if electricity costs increase it would improve the IRR of the systems.

Weniger et al. (2014) studied optimal sizing of integrated PV-battery systems in Germany. Their study identified optimal battery capacity for PV-battery systems in the future by incorporating investment cost and FIT cost factors. It was found that the integrated PV-battery storage systems will tend to have a smaller scale battery storage capacity with higher-self consumption rates. Their study claimed that the investment in PV-battery systems would be economically justifiable when the average electricity price of the systems became lower than the mean price of purchased electricity from the grid. As large battery capacity requires high investment costs, which increases the mean electricity price of PV-battery systems, optimal battery sizing will tend toward small-scale battery capacity to make the systems economically profitable.

Weniger et al. (2014), further, studied the break-even point of battery price for PV-battery systems in Germany. The study found that PV-battery systems would show positive economic return if the battery systems costs are below 1,160€/kWh. However, the break-even price could vary depending on the input parameters. Their study identified that interest rate, PV-battery systems cost, electricity retail cost, and FIT price were the major factors that influenced the profitability of the systems. Moreover, uncertainties associated with PV-battery systems such as annual electricity demand of households and electricity consumption pattern could impact the result of profitability analysis.

Naumann et al. (2015) studied the cost analysis of optimal battery capacity for integrated PV-battery systems in Germany. Their study focused on the impact of electricity price and battery cost to the overall profitability of PV-battery systems. The results showed that PV-battery systems only showed positive return on investment if an additional incentive, 50 €/kWh of stored energy, was introduced. The study claimed that the additional incentive might not be needed in the future if the cost of electricity increases and the cost of batteries decreases.

Bruch and Muller (2014) studied the cost effectiveness of integrated PV-battery systems in Germany. A rationale behind the study was that the high cost of battery storage systems and the inadequacy of optimal PV-battery configuration could lead to a negative return on investments; thus, it was noted that it is important to understand the most economically feasible PV-battery configuration including battery storage size. The study found that the high investment cost of battery systems reduced the overall profitability of integrated PV-battery systems. The research proposed a need for policy incentives on storage to improve the profitability of the systems. Their analyses, however, confirmed that even with the subsidy, which was 600 €/kilowatt (kWp), the economic profitability of PV systems without a battery was twice as much as that of PV-battery systems. To avoid economic losses from an investment on PV-battery systems, the design of the optimization of the systems should be examined individually by verifying economical and technological performance of the systems that meet the requirement of each customer.

The study also analyzed the most profitable battery type to be used for the residential PV system among redox flow batteries, lead-acid batteries, and lithium-ion batteries. It was found that the most profitable battery type was redox flow batteries followed by lead-acid batteries. The study showed that lithium ion batteries presented the least financial value because it was the most expensive battery among the three. However, the researchers expressed the view that lithium ion batteries may become a preferred choice in the future, as the cost of lithium ion batteries would likely be lower in the future.

The study by Graebig et al. (2014) stated negative views on the use of PV-battery systems. In spite of the previously reviewed studies, which presented options and scenarios to make PV-battery systems economically profitable, Graebig et al. (2014) concluded that integrated PV-battery systems, 7kWp PV system and 4kWh battery system, are unlikely to be a cost-efficient option in Germany. Their study confirmed that due to the high cost of the systems, only 1/4 to 1/3 of the initial investment could be compensated during the systems' lifetime. The study forecasted that the systems may become cost-efficient in the future if the electricity price increases, the FIT is abolished and/or the cost of batteries decreases. Moreover, they claimed the need for a new incentive, such as an incentive for PV-battery systems to be used under electricity outage circumstances; otherwise it was noted that there was no need of PV-battery systems in Germany due to the country's mature electricity infrastructure. The authors suggested that performing the same study in other countries or regions might show different outcomes.

Their study is unique as it studied perceptions of the value proposition of the systems. From 2,134 surveys, they found that consumers tend to install PV-battery systems in hopes to reduce their electricity bills; however, their willingness to buy the systems do not match with the realistic payback period of the systems (Graebig et al., 2014).

Among several studies on integrated residential PV-battery systems, studies performed by Hoppman et al. (2014) and Cucchiella et al. (2016) can be categorized as the most advanced in academic journals. Their studies assessed the potential of integrated PV-battery systems without any policy incentives or premium incentives for electricity generated from PV or self-consumption. While the impacts of subsidy programs are significant, the research concluded that these impacts would weaken in the future. Policy incentive mechanisms such as FIT, premiums for self-consumption electricity generated from PV and investment subsidies for PV-battery systems are used as short-term supplements to support the deployment of the systems in the market so that they become payable without any subsidies in the future. Their studies can be regarded as leading studies in assessing when and under what conditions the systems become economically viable without any policy support.

Hoppman et al. (2014) used techno-economic analyses to study when and under what conditions PV-battery storage systems could be economically justifiable in the German residential sector. They assessed the economic profitability of PV-battery systems from the period of 2013 to 2022. The authors claimed under no demand-side incentives, wholesale price, which is the price of electricity sent out to the grid, and retail price, which is the price of electricity purchasing from the grid, were the two key factors that affect the economic variability of PV-battery systems with no new policy incentives. The study set eight scenarios from wholesale price and retail price to analyze different outcomes based on 2013 wholesale price and retail price, which were 0.042€/kWh and 0.288€/kWh, respectively.

It was found that an increase in the electricity retail prices and a decrease in the cost of wholesale electricity could contribute to push up the profitability of the systems over the long-term. The study further expected that the optimal sizing of integrated PV-battery systems would become larger in the future if households could gain access to the wholesale electricity market.

Similar to Hoppman et al. (2014), Cucchiella et al. (2016) conducted a study on the economic profitability of integrated PV-battery systems in the Italian residential sector without any subsidies. The study focused on assessing the economic profitability of the systems under a situation which the systems were used to maximize self-consumption rates.

Their study, however, drew an opposite conclusion from Hoppman et al. (2014). From the analysis of 3,456 scenarios, they concluded that in the Italian residential market, integrated PV-battery systems were not a cost effective option without incentives, as all the scenarios showed the unprofitability of the systems because the revenues from the amount of self-consumption could not compensate the investment costs of the systems. Furthermore, the study articulated that PV size, battery size, electricity cost, tax deductions, insolation level, self-consumption rate, and battery life were the key factors in making the systems economically profitable.

It is important to note that both Hoppman et al. (2014) and Cucchiella et al. (2014) used lead-acid batteries, which are available in relatively lower price than lithium ion batteries. The study might have drawn a different conclusion, if lithium ion batteries were used in the assessment.

2.3 PV-battery systems study in Japan

While a number of academic studies have been conducted internationally, only a limited number of academic studies on integrated PV-battery systems in Japan are available today. Some of the available literature focuses on the technological aspects of integrated PV-battery systems. Shimada and Kurokawa (2006) studied the concept of a forecast system to analyze the effectiveness of integrated PV-battery systems. They assessed the effectiveness of insolation forecasting and battery control technologies for grid connected residential PV-battery systems. Such methods enabled to calculate the following day's amount of sunlight to estimate the appropriate amount of electricity that needed to be charged to a battery at night. The study confirmed that insolation forecasting system proved to be a cost effective and an energy efficient option for PV-battery systems.

NEDO conducted a project in Japan called, "Demonstrative Project on Grid-interconnection of Clustered Photovoltaic Power Generation Systems" in 2002 in the City of Ota to test the grid stabilization of large-scale PV power generation systems (NEDO, n.d.). This project was conducted to analyze the impact on grid stability of having more than 500 residents install grid-connected PV-battery systems. Lead-acid batteries were used together with the PV systems to analyze their impacts on the grid system. Some academic articles on this project are available, such as Ueda et al. (2006) and Ueda et al. (2008), which summarized the technological findings of the project. It was found that the overall performance of PV-battery systems recorded 8% lower than that of PV systems without a battery. The main reason for the decrease in the total performance of PV-battery systems was due to the losses from the battery and the power conditioning system (PCS).

In contrast to the above-described studies, Yamaguchi et al. (2003), Iga et al. (2004), and Yoshida et al. (2016) focused their studies on the economic aspects of grid-connected residential integrated PV-battery systems. Yamaguchi et al. (2003) conducted a study to find out an optimal sizing of integrated PV-battery systems that could maximize the economic returns of homeowners. The study concluded that an optimal PV-battery systems configuration was 3 kW or 5 kW PV capacity and about 10 kWh battery capacity. Such systems were able to meet most of the electricity demand of the study houses between 7 am and 11pm. It was also identified that integrated PV-battery systems could generate about additional 20,000 yen/year profits than PV systems without a battery. In addition, while the break-even point of PV systems without a battery was 650,000 yen/kW, PV-battery systems increased the break-even point to 750,000 to 800,000 yen/kW. Their study presented the effectiveness of using PV-battery systems.

A study by Iga et al. (2004) further analyzed optimal battery sizes that could maximize economic returns and compared the results of five different locations in Japan, which were Tokyo, Osaka, Akita, Takamatsu and Kagoshima. The result presented that while optimal battery sizes in five locations were relatively the same, which ranged from 6 to 8 kWh, annual economic return could vary from 10,000 yen to 20,000 yen/year depending on the location of where the systems were installed.

While Yamaguchi et al. (2003) and Iga et al. (2004) used lead-acid battery as a potential battery type in their analyses, Yoshida et al. (2016) used lithium ion battery for their study. Their study holds a value as an academic study because studies that focus on integrated PV-plus-lithium ion battery storage in the Japanese residential sectors are minimal and limited in availability. They studied the economics of residential grid-connected integrated PV-battery systems; more specifically, they investigated the cost savings and the energy savings of PV-battery systems in Japan. It was found that while PV systems without a battery could save 1.15 million yen over ten years compared to a conventional scheme with houses fully depend on electricity from the grid, PV-battery systems could only save additional 0.1 million yen in 10 years compared to the PV systems without a battery. The study, therefore, concluded that PV-battery systems were not as cost effective as PV systems without a battery.

In terms of energy savings, it was evident that PV-battery systems were able to save 145 GJ compare to PV-systems without a battery. This leads to the conclusion that integrated PV-battery systems had more impact on the energy saving than on the cost saving.

Yoza et al. (2014) assessed the value proposition of integrated PV-battery systems in the Japanese residential sector. They conducted an analytical study to assess whether PV-battery systems in a smart house would be capable in returning sufficient economical values over a 20-year period, from 2015 to 2035. The study prepared a hypothetically setting in Okinawa, Japan, where the place records strong solar intensity. This study is unique as it also presented the best year to install PV systems and/or battery systems within the investment period by estimating future costs of the systems. To ensure variability, the study set four different scenarios: (1) a house that neither installed PV panels nor a battery system; (2) a house that installed only a PV system; (3) a house that installed only a battery system; and (4) a house that installed both PV and battery systems.

According to their analyses, the most economically feasible option was installing only a PV system, which the system expected to produce 178,000 yen over the investment period. Optimal installation year of the systems was 2015. The PV-battery systems also showed positive return on investments; however, the return was lower compared to return from installing only a PV system, which was 49,000 yen. In this case, the study presented optimal investment year of 10 kW PV systems in 2015 and 1 kWh battery systems in 2034, when the cost of battery is expected to reach about 20,000 yen/kWh. The study also concluded that both a resident with neither PV panels nor a battery storage and installing only a battery, 6 kWh capacity, in a house were not a cost-beneficial option, as these options showed negative return on investments, which were -3,580,000 yen and -3,440,000 yen, respectively.

There are, however, some important findings that can be highlighted from the study. The study estimated the optimal system configuration of integrated PV-battery systems, which was set at 10 kW PV capacity and 1 kWh battery capacity. The optimal capacities that were applied in the study, however, do not reflect the current trends of residential capacity of the systems. According to Japan Photovoltaic Energy Association (JPEA), the average capacity of solar PV installed at houses in Okinawa in 2014 was 5.42kW. 10kW capacity could be considered as overcapacity. In addition, 1kWh battery capacity could be regarded as lack of capacity, as many of residential battery storage systems today are available at the capacity of more than 5kWh. Moreover, it is unclear the type of battery used in the study. Thus, there is a potential for studying the monetary benefits of integrated PV-lithium ion battery systems in Japan that incorporate realistic PV and battery capacities.

2.4 Battery storage systems

Many technologies are available today to store electrical energy, such as battery, pumped hydroelectric storage, compressed air energy storage, fuel cell, flow battery, solar fuels, superconducting magnetic energy storage, flywheel, capacitor, and thermal energy storage (Chen et al., 2009). Among different types of electric energy storage technologies, battery is considered an ideal technology to store energy. Until today, significant development has been made in battery technologies. As a result, different types of batteries have been invented, in which some are commercially available today while some are still under the full development stage (Divya & Østergaard, 2009).

Energy storage devices require constant charge and discharge of energy. Batteries are generally preferred, because they can meet such requirement in a rapid manner, which contributes to the stability of the electricity system. They also have low standby losses and they can operate with higher energy efficiency rate, at about 60 – 95% compared to other electric storage technologies (Chen et al., 2009).

2.5 Types of battery storage systems

Batteries can be mainly categorized into five major types: (i) lead acid battery; (ii) nickel cadmium battery; (iii) sodium sulphur battery; (iv) sodium nickel chloride battery; and (v) lithium ion battery. Table 2 on page 33 and 34 summarizes the characteristics of each of the batteries.

2.5.1 Lead acid batteries

Lead acid batteries are the oldest type of batteries which were invented in 1859. These are a mature technology and are mostly used in mobile and stationary applications (Khaligh & Li, 2010 & International Electrotechnical Commission, 2011). Some advantages of the lead acid batteries are (i) availability at a low cost of

$300 – 600/kWh and (ii) high reliable performance and high efficiency rate of 70 – 90% (Chen et al., 2009). Although, a short life cycle period, which is about 1,000 – 2,000 cycles and a low energy density, which is about 25 – 50 Wh/kg, are some drawbacks, they were once preferred as small-scale residential batteries (Divya & Østergaard, 2009, Hoppmann et al., 2014). One of the major drawbacks is that their performance degrades at low temperatures, thus requiring a heat management system to maintain high operational performance (Chen et al., 2009).

2.5.2 Nickel cadmium batteries

Nickel cadmium batteries are also one of the oldest types of batteries. Their typical applications are in power tools, portable devices, emergency lighting, uninterruptible power supply, telecoms and generator staring (Chen et al., 2009). They are the only types of batteries that perform without degradations at a low temperature of up to -40 °C (International Electrotechnical Commission, 2011). Both lead acid batteries and nickel cadmium batteries have high reliability performance; but nickel cadmium batteries have a higher efficiency than lead acid batteries, in which energy density is about 55 Wh/kg (Khaligh & Li, 2010). They require low maintenance and have a greater life cycle compared to lead acid batteries, which is about 3,000 cycles (Divya & Østergaard, 2009). The biggest drawback, however, is the price: nickel cadmium batteries can cost up to $1,000/kWh (Chen et al., 2009).

2.5.3 Sodium sulphur batteries

Sodium sulphur batteries are used for combined power quality and peak shift applications (International Electrotechnical Commission, 2011). One of the famous sodium sulphur batteries is NaS battery. A Japanese company, NGK INSULATORS, LTD., was the first company to successfully start a mass production in 2003 (NGK INSULATORS, LTD., n.d.) Since then, it has been installed in more than 200 places in Canada, Japan, Germany, France, U.S.A. and UAE for peak cut and peak shift purposes (International Electrotechnical Commission, 2011 & NGK INSULATORS, LTD., n.d.).

A NaS battery is mainly used for storing a large volume of electricity. Its characteristics are: (i) high response speed, which is in the range of milliseconds; (ii) high energy savings capacity, which is an average of 300 kWh to 360 kWh in one module; (iii) ability to store a high volume of energy in a smaller size, approximately 1/3 of the size of lead acid batteries; (iv) its typical life cycle is about 4,500 cycles; (v) high energy density of 150 – 240 Wh/kg; (vi) high power density of 150 – 230 W/kg; and (vii) high efficiency rate of 75 – 90 % (Chen et al., 2009, International Electrotechnical Commission, 2011 & NGK INSULATORS, LTD., n.d.). Since NaS batteries must be kept at the temperature of 300 – 350 °C to operate, they require a heating system, and result in high installation costs of about $35/kWh, which can be considered as one of the drawbacks. This technology is viewed as a potential solution to electric companies or large consumers to install for grid stabilization as the use of renewable energy sources increase (International Electrotechnical Commission, 2011).

2.5.4 Sodium nickel chloride batteries

Like NaS batteries, sodium nickel chloride batteries, also known as the ZEBRA batteries, can be categorized as high operating temperature batteries, as they operate at a temperature of around 270 °C (Meridian International Research, 2005, Chen et al., 2009 & International Electrotechnical Commission, 2011). Their applications are for buses and commercial vehicles; but their technology is highly regarded today for use in hybrid and electric vehicles (Bull, & Tilley, 2001 & Meridian International Research, 2005). The biggest advantage of this battery is that it can operate over a wide range of temperatures, from -40 to 70 °C. Its energy and power density is about 120Wh/kg and up to 150 W/kg, respectively (Chen et al., 2009). The Zebra batteries are perceived as potentially suitable for use in electric vehicles. The biggest drawbacks, however, are uncertainty in meeting demands and the unlikeliness of availability in lower costs since only a Swiss based company, MES-DEA GmbH, can produce this type of battery (Meridian International Research, 2005 & Chen et al., 2009).

2.5.5 Lithium ion batteries

Among different types of batteries, lithium ion batteries have received increased attention in recent years. Initial lithium ion batteries were introduced in 1960s', but the first commercial batteries were produced in early 1990s by a Japanese company, Sony Energy Devices Corporation, a subsidiary of Sony Corporation (Dunn, Kamath, & Tarascon, 2011 & Sony Energy Devices Corporation, 2016). Since then, vast investments in the development of lithium ion batteries have been made. As a result, they are now used in more than 50% of small portable applications, such as computers, mobile phones and electric bicycles and vehicles (Chen et al., 2009 & International Electrotechnical Commission, 2011). The biggest advantages of lithium ion batteries are: (i) high energy density; (ii) long life cycle; and; (iii) high efficiency. Their energy density is about 200 Wh/kg, with maximum life cycles of about 10,000 and 95 – 98% efficiency rate (Chen et al., 2009 & International Electrotechnical Commission, 2011). Moreover, lithium-ion batteries do not require as much maintenance as lead acid batteries and Nickel cadmium batteries do (Nair & Garimella, 2010).

The Department of Energy (DOE) in the United States of America (USA) compiled lithium ion battery projects from around the world. According to the DOE, currently, 434 lithium ion battery projects are reported globally. While some of these projects are already in operation, some are expected to come into operation in the near future. Project capacities range from small-scale sizes, which are less than 10 kW, to larger scales, up to 100 MW. These batteries are used for various purposes: to shift electricity peak demand, to regulate electricity frequency, to increase the capacity of electric supply, to increase the capacity of electric supply reserve, to support voltage stability and to initiate demand response.

Yet, they still experience some challenges: one of the issues is high cost, due to complex manufacturing processes required to ensure safety of the components (Divya & Østergaard, 2009). This is the largest obstacle for lithium ion batteries to be used in larger applications. The cost, however, is expected to decrease in the future for use in large-scale applications due to ongoing technology development and the expectation for high demand use (Nair & Garimella, 2010). IRENA calculated the expected future costs of utility-purpose lithium ion batteries to decrease from USD$ 550 in 2014 to USD$ 300 in 2017 and USD$ 200 in 2020 (2015). The decline in the cost of batteries can be an advantage for them to be used in larger size applications, such as for residential storage batteries.

2.6 The relationship between lithium ion batteries and the residential sector

A decrease in the cost of lithium ion battery increases its potential for use as a battery storage device. Lithium ion batteries have been considered as the most appropriate option for use in residential energy storage applications due to their high performance and high reliability aspects (Darcovich et al., 2013). Their high energy density, high life cycle rate and high efficiency rate outperform lead acid batteries for use in the residential battery storage applications (Scrosati & Garche, 2010). For instance, the net zero energy homes in U.S.A and Canada and eco houses in the Fujisawa Sustainable Smart Town in Japan, in which both PV solar and battery storage systems are installed, present potential use of residential battery storage systems as a cutting edge solution for future residences.

Integrated together with a PV system, a residential battery storage system is expected to offer several advantages to the users, such as decreasing the total load of grid power and reducing the cost of electricity bills by increasing self-generation and self-consumption rates (Panasonic Eco Solutions Canada Inc., n.d.). In addition, they allow homeowners to have control over their electricity consumption pattern and can contribute to using renewable energy resources more efficiently (Nair & Garimella, 2010). However, in order to ensure such benefits are delivered to the users, systems must be economically feasible: the electricity cost savings must be higher than the installation cost of battery storage systems (Naumann et al., 2015).

Table 2: Overview of the five battery types

Types of battery	Application	Advantage	Disadvantage
Lead acid	Mobile and stationary applications	• Mature technology • Low cost ($300 – 600/kWh) • High efficiency rate (70 – 90 %) • High reliability	• Short life cycle (1,000 – 2,000) • Low energy density (25 – 50Wh/kg) • Performance deteriorates at a lower temperature
Nickel Cadmium	Power tools, portable devices, emergency lighting, uninterruptible power supply, telecoms and generator staring	• Mature technology • Ability to operate in temperatures up to -40 °C • Higher energy efficiency (55 Wh/kg) than lead acid batteries • High reliability • Low maintenance	• High cost ($1,000/kWh) • Short life cycle (3,000)
Sodium sulphur (NaS)	Large size applications for peak cut and peak shift purposes	• Fast response speed (milliseconds) • High energy capacity (300 kWh to 360 kWh/module) • Ability to store high volumes of electricity in a smaller size (1/3 of the size of lead acid batteries) • High energy density (150 – 240 Wh/kg,) • High power density (150 – 230 W/kg) • High efficiency rate (75 –	• Requires heating system due to high operating temperature (300 – 350 °C) • High cost ($35/kWh)

		90%) - Longer life cycle (4,500)	
Sodium nickel chloride (ZEBRA)	Buses and commercial vehicles Hybrid and electric vehicles	- Ability to operate in a wide range of temperature (-40 to 70°C) - Energy density of 120 Wh/kg - Power density of 150 W/kg	- Uncertainty in meeting demands - Uncertainty in lowering costs
Lithium ion	Small portable applications (computers, mobile phones and electric bicycles and vehicles)	- High energy density (200Wh/kg) - High efficiency (95 – 98%) - High life cycle (10,000)	- High cost

2.7 Net present value (NPV) and Internal rate of return (IRR)

Prior to making an investment, regardless of the size of an investment, a company is encouraged to assess the risks and expected profits of a project over time. Several investment indicators are used according to their needs to assess the possibility of an investment. NPV and IRR are most widely used evaluation techniques, especially by financial institutions and investment offices in companies. Graham & Harvey (2001) conducted a survey to 392 chief financial officers (CFOs) to find out the most commonly used capital budgeting method. According to their study, 74.9 % of survey respondents answered that they use NPV as the most frequently used technique; and 75.7% of the respondents claimed that they use IRR the most (2001).

Both NPV and IRR belong to the discounting criteria in the investment criteria (Bora, 2015). They take into consideration the time value of money factor in evaluating projects; and they are highly regarded as the most important criteria in practice (Bora, 2015). Their differences, however, are that NPV is used to assess expected return of an investment in the present value (PV), while IRR is used as a yearly average earning rate indicator, thus NPV is described in monetary bases and IRR is indicated in percentages.

In academic literature, several studies used NPV and/or IRR as an evaluation tool to examine the economic performance of integrated PV-battery systems. Table 3 provides information on authors who used NPV and/or IRR in their studies and what assessment techniques they used. It is a frequent practice to use NPV and IRR in papers when studies try to validate the economics of certain topics.

Table 3: Authors who used NPV and/or IRR in their studies

Authors	Measurement
Braun et al. (2009)	IRR
Colmenar-Santos et al. (2012)	NPV & IRR
Hoppman et al. (2014)	NPV
Cucchiella et al. (2016)	NPV

2.7.1 Net Present Value (NPV)

NPV is regarded as the most theoretically reliable economic profitability assessment methods (Cuthbert & Magni, 2016 & Shil, 2009). As a part of the discounted cash flow (DCF) analysis, NPV can evaluate an investment by comparing the current investment cost and expected future cash flow from the investment converted in PV (Shil, 2009).

NPV presents how much money would be either gained or lost from investing in a project. If the results show NPV < 0 or negative NPV, it is not worthwhile to invest in a project, because it is expected to result in loss; on the other hand, if calculations present NPV > 0 or positive NPV, it justifies to invest in a project, as the project is expected to create a financial surplus (Blas, 2006).

2.7.2 Internal Rate of Return (IRR)

According to the book, "Investment Performance Measurement" by Feibel, IRR is categorized as part of the Money-Weighted Return (MWR) (2003). MWR allows calculation of expected profit over a certain time, which investors use as one of the references to identify the risks associated with a project and assess the legitimacy to invest in a project. IRR, an indicator of the MWR, is used as a profitability indicator and is used to measure the expected profit of an investment in a percentage format (Aho & Virtanen, 1983; Milis & Mercken, 2004).

IRR is defined as “the rate of discount which equates the present value of the net cash flows from the investment with its initial capital expenditure” (Aho & Virtanen, 1983, p. 256). IRR is often considered as a better investment indicator compared to the payback period (PP) and the return on investment (ROI), because it considers the time and value of money by using a discount rate (Feidel, 2003; Milis & Mercken, 2004). IRR refers to the total growth in value of assets invested in over the selected period of time under assessment (Feidel, 2003). IRR has been recognized as a suitable statistic approach for measuring and assessing investments, such as investment projects related to information security (Gordon & Loeb, 2002). In addition, it has been commonly used in Private Finance Initiative (PFI) schemes in UK to measure the performance of projects (Cuthbert & Magni, 2016).

In IRR, a hurdle rate has to be set for each project. The hurdle rate is the permissible minimum rate of return on an investment project set by an investment institution or an investor. If the result of IRR is smaller than the set hurdle rate, then a project does not have sufficient value for an investment; on the other hand, if IRR is larger than the set hurdle rate, a project is considered as worthwhile to invest in. It is believed that higher IRR, the more desirable a project is to invest in. IRR has been highly regarded in projects related to renewable energy to be used as one of the indicators for making an investment decision. In the article “Top 10 reasons to invest in renewable energy projects”, O’Connor says average IRR on renewable energy projects is between 6 to 8% (2013).

Multilateral financial institutions have commonly used IRR as part of the evaluation process to assess potential projects. For example, both the African Development Bank (AfDB) and the Inter-American Development Bank (IDB) set higher hurdle rates for their projects, at 10 – 12% and 12%, respectively, compared to other multilateral financial institutions (Asian Development Bank, 2013). The European Investment Bank (EIB) and the European Commission (EU) set lower hurdle rates, which are about 3 – 5% lower than AfDB and IDB (Asian Development Bank, 2013). In the case of the Asian Development Bank (ADB), they are considering to reduce the current IRR rate of 12% to 6%, which is the same hurdle rate set by the World Bank (WB) (Asian Development Bank, 2017 & Asian Development Bank, 2013). Appropriate hurdle rates, however, to approve projects differ by the types of projects including types of renewable energy sources and each decision maker or institution.

2.7.3 The relationship between NPV and IRR

NPV and IRR both have some disadvantages, such as NPV lacks in presenting information regarding the timespan of a project to create financial returns and IRR lacks in considering risks associated with a project, thus neither measure should be used as a tool to select exclusive projects (Milis & Mercken, 2004 & Kaushal, 2015). Unlike NPV, IRR can incorporate only one discount value, thus it cannot be used in the situation if the discount rate changes during a project cycle (Kaushal, 2015). In such cases, NPV and/or Modified Internal Rate of Return (MIRR) should be preferably used. Although IRR is commonly used and preferred among experts due to ease in seeing the result in the percentage format, IRR does not take into account the size of projects; thus, it should not be used to compare the results of projects that differ in sizes (Milis & Mercken, 2004).

If the project is either independent or only has a single investment, the results of NPV and IRR calculation usually result in the same investment decision (Bora, 2015). A project denied by the NPV analysis shows lower IRR and a project that shows return in profit by the NPV analysis shows higher IRR. However, there are occasions in which the results of NPV and IRR are mutually exclusive. For example, if one wants to compare the investment potential of Table 4, the results of NPV and IRR do not match. In such cases, an investment decision should be made by comparing the NPV values. Thus, in the case of Table 4, Project A should be prioritized over Project B even though the IRR value of Project A is lower than that of Project B. In the world of finance, it is believed that the NPV should take a leading role and IRR should be used for a supplemental purpose, because NPV focuses on the value maximization of an investor or a company through an investment (Shil, 2009 & Bora, 2015).

Table 4: Example of NPV and IRR in two projects

Project A	$1,500	10%
Project B	$500	15%

Created by the author

2.8 Sensitivity analysis

Sensitivity analysis is a part of capital budgeting; it is used to analyze the impact on calculated NPV when preconditions of a project changes such as initial cost, running cost or market sizes (Corporate Finance, 2008). Investment projects are composed of many different factors. The profitability of a project is affected even if one input parameter changes. Graham & Harvey claimed companies tend to conduct sensitivity analysis that together with NPV and IRR analysis to meet regulatory requirements. Sensitivity analysis allows unveiling how sensitive NPV is, if the key variables of the preconditions of a project change (Corporate Finance, 2008). In academic literature, it is evident that sensitivity analysis has been used often. From academic literature similar to this study, Braun et al. (2009), Colmenar-Santos et al. (2012), Hoppman et al. (2014), Weniger et al. (2014) and Cucchiella et al. (2016) conducted a sensitivity analysis to examine how output parameters affects by manipulating input variables.

Chapter 3: Background

3.1 Introduction

This section provides information about Japan's energy mix before and after 2011, its renewable energy portfolio and the introduction of FIT scheme and its activities on residential PV and PV-battery systems to provide the context for the study. Japan's energy situation has changed since the Great East Japan Earthquake in 2011. After the incident, the country paved a new path to integrate renewable energy sources into the country's energy mix. As a result, the use of PV generation in the Japanese residential sector has grown rapidly.

3.2 Energy mix in Japan before 2011

The energy condition in Japan is unique relative to the rest of the world. Japan is an island nation surrounded by oceans: the Sea of Okhotsk, the Pacific Ocean, the East China Sea and the Sea of Japan. Japan does not share land borders with any country. The country's lack of energy resources makes it a vulnerable nation that recognises the importance of energy security. Due to its limited resources, Japan has been relying heavily on imports from overseas for its energy resources. While Japan is the fourth-largest country in terms of GDP, the country ranks as one of the lowest primary energy self-sufficient country within the OECD countries, accounting only 19.9% in 2010 (Agency for Natural Resources and Energy, 2016). Thus, energy policies in Japan have been based on securing energy supply while minimizing its dependence on imports. In 2008, the country's largest source of energy in the energy mix was coal, which was 27%, followed by 26% from natural gas, 24% by nuclear and 13% from oil. The remaining 10% was from renewable energy sources and others in which hydroelectric power dominated most of this share, followed by biomass generation (METI, 2016).

To mitigate the country's vulnerability in energy security, the Japanese government promoted the use of nuclear power as a base-load energy resource. In 2010, 28.6% of electricity was generated by nuclear power (METI, 2014), which ranked the country as the third largest nuclear power producer after USA and France (The U.S. Energy Information Administration, 2015). As a result, the electricity generated through nuclear power plants became the cheapest source of electric power (EIA, 2015). To ensure the country's energy security, the Japanese Basic Energy Plan in 2010 set a target of increasing its nuclear power generation capacity up to 50% of its total electricity generation by 2030 (OECD, 2013).

3.3 The Great East Japan Earthquake in 2011 and its impact on Japan's energy system

The Great East Japan Earthquake in 2011 resulted in nuclear meltdown at the Fukushima Daiichi nuclear power plant, causing extensive damage to Japan's energy supply mix. The nuclear meltdown changed the country's overall energy mix drastically. The operations of all 54 nuclear power plants were shut down, which accounted for nearly 30% or 46,148 MW of the total energy production (The Federation of Electric Power Companies of Japan, 2016). The incident resulted in three major consequences.

The first is that Japan has been forced to rely on imports of energy sources from overseas once again, which re-exposed the country to vulnerability in its energy security. Natural gas generation compensated for most of the loss from foreclosure of nuclear power plants. Electricity generation from natural gas increased from 29% in 2010 to 48% in 2012 (Agency for Natural Resources and Energy, 2014). Japan's current dependence on carbon sources for electricity generation makes the country the largest importer of natural gas, the second largest importer of coal and the third largest importer of crude oil in the world (EIA, 2015). The report from the Ministry of Economy, Trade and Industry (METI) in 2015 noted that the use of imported fuel in total power generation was recorded at 88% in 2013 (Yoshino, 2015). As a result, the country's primary energy self-sufficient rate decreased to 6% in 2012, which placed the country as the second lowest primary energy self-sufficient country within the OECD countries (International Energy Agency, 2015).

Secondly, its high dependence on fossil fuel generation caused tremendous decrease in the account balance, resulting in the worst trade deficit of 13.8 trillion yen due to an increase in imports of oil. Of the 13.8 trillion yen, seven trillion yen was spent on natural gas imports (Agency for Natural Resources and Energy, 2014). Moreover, electricity price increased by approximately 25% in the residential sector and nearly 40% in the industrial sector due to higher fuel costs for thermal power generation (Agency for Natural Resources and Energy, 2014).

The third consequence was the increase in GHG emissions from the energy sector. In fiscal year 2013, total GHG emissions reached 1.224 billion metric tonnes of carbon dioxide equivalent (Mt CO2e), the highest level ever recorded (Iwata, 2015).

3.4 Energy transition in Japan

The incident of the Great East Japan Earthquake in 2011 forced the country to revisit the Japanese Basic Energy Plan released in 2010. In addition, the country is also challenged to consider climate change in the new energy plan. Today, the issue of climate change has become a global priority. The Fifth Assessment Report (AR5) by the Intergovernmental Panel on Climate Change (IPCC), released in 2014, provided a detailed overview of the current state of climate change. According to the report, in order to maintain a global warming of below 2°C compared to the pre-industrial levels or CO_2-equivalent concentrations of 450 ppm or lower by the end of 21st century, 40 to 70% reduction in GHG emissions by 2050 and further, almost zero or lower emissions by 2100 are required (IPCC, 2014).

At COP21 in Paris in 2015, 195 countries agreed to an international legally binding agreement on climate change for the first time in history. This agreement comes in effect in 2020 and holds each of the participating countries equally responsible to maintain the global average temperature to within 2°C above the pre-industrial levels. Of all the contributing sectors, the energy sector accounts for approximately 60% of the total emissions in the world. Thus, taking measures to reduce the GHG emissions from this sector are vital to achieve the agreed goal (Sustainable Energy for All, n.d.).

Japan ranks as the 6th largest GHG emitter in the world (Ge et al., 2014). As one of the largest contributors to climate change, at COP21, Japan committed to reduce its GHG emissions by 26% by 2030 compared to the 2013 level, equivalent to 1,042 Mt CO2e reductions by 2030 (UNFCCC, 2015). To meet this commitment, the Japanese government announced a new long-term energy plan, Long-term Energy Supply and Demand Outlook, in 2015. This plan forecasts the country's new energy mix in 2030.

3.5 Japan's new energy supply mix

The Long-term Energy Supply and Demand Outlook in 2015 presents a noticeable outcome which is to restart the operations of nuclear power plants for use as a base-load energy resource to improve its low energy self-sufficient rate. Despite the fact that the Fukushima nuclear disaster was the largest nuclear accident since Chernobyl disaster in 1986, and the second case to be given the Level 7 event classification of the International Nuclear Event Scale, the Japanese government still considers the use of nuclear power plants as the base-load energy resource. The report estimates that the cost of electricity from nuclear generation in 2030 will remain as the cheapest source of energy with at least 10.3yen/kWh (METI, 2015). The decision to restart the operation of nuclear power plants was made despite weak public support after the incident in 2011. According to a public opinion survey held in October 2016, 57% of the respondents opposed the restart of the operations of nuclear power plants; on the other hand, only 29% of the respondents agreed to resume the operations of nuclear power plants (The Asahi Shimbun Company, 2016).

To prevent future accidents similar to the Fukushima nuclear disaster and to gain public trust, the country set a new regulation in 2013 imposed by Japan's Nuclear Regulation Authority (NRS) (Hayakawa, 2015). The guideline outlines strict safety regulations applicable to all nuclear power plants considering resuming operations, in regards to natural disaster events, such as tsunami and seismic events, power loss at the station and the state of emergency preparedness. The new NRS guidelines demand one of the highest safety measures in the world. As of June 2017, 12 out of 42 reactors have met the new guidelines and four nuclear power plants have resumed operation (Nuclear Energy Institute, 2017).

3.6 Renewable energy portfolio in Japan’s new energy mix

Due to the suspension of nuclear power plant operations after the Fukushima incident in 2011, Japan’s energy mix shifted to a higher dependence on imported fossil fuel sources, which worsened Japan’s GHG emissions. To address this issue, the new long-term energy plan offers an increase in the use of renewable energy sources in the total energy mix. With the new plan, Japan aims to have 22 - 24% of its total energy supply mix from renewable energy sources: 7.0% from solar generation, 1.7% from wind, 1.0 - 1.1% from geothermal, 8.8 - 9.2% from hydro and

3.7 - 4.6% from biomass in 2030 (METI, 2015). It is expected that PV generation will increase sevenfold by 2030, compared to the 2013 level (METI, 2015).

With policies in place that support both resuming the operations of nuclear power plants and including a larger share of renewable energy resources to the energy mix, Japan aims to achieve around 25% primary energy self-sufficient rate by 2030 (Ministry of Economy, Trade and Industry, 2015).

3.7 The introduction of a new FIT scheme in Japan

The primary reason for a substantial increase in the use of PV generated energy by 2030 compared to 2013 is the newly established FIT program. In 2012, the Japanese cabinet approved the “Act on Purchase of Renewable Energy Sourced Electricity by Electric Utilities,” or a FIT program to increase the installation of renewable energy technologies or systems across the country (METI, 2011). With this program, electric utility companies are mandated to purchase electricity generated from renewable energy resources, which are photovoltaic, land-based wind, offshore wind, geothermal, hydropower in 200kW to 30,000kW capacity and biomass, at a fixed price that is set for each type of renewable energy.

FIT is the most widely used program worldwide, to increase the use of renewable energy resources. It has been implemented in 108 national and local governments globally (Renewable Energy Policy Network for the 21st Century, 2015). Although, the design details of FIT, such as contracted prices and guaranteed purchase periods, varies by region, the general purpose of the program is to boost the output from renewable energy technologies and to decrease the installation costs of renewable energy technologies. Japan's new FIT program is especially targeted for solar and wind power installations. Since 2012, the amount of renewable energy that was integrated into the energy grids increased substantially, by over 30%. Majority of the renewable energy source is from PV generations in the residential and non-residential sectors (Yamazaki, 2015).

3.7.1 2009 FIT program

The Japanese government introduced the PV surplus electricity purchase system under the Act on Sophisticated Methods of Energy Supply Structures in 2009, which allows individual electricity producers to sell the electricity generated from the residential and commercial solar PVs, that are less than 500kW capacity, to electric utility companies (Maeda et al., 2011; New Energy and Industrial Technology Development Organization, 2014). However, by 2011, the share of renewable energy sources, except for hydroelectricity, in the total energy mix remained less than 1% (Yamaguchi, 2013). This is mainly due to the monopolized structure in the generation, transmission and distribution of energy controlled by 10 regulated authorities for over 50 years, being a bottleneck in accepting electricity generated from a third party. Moreover, the monopolized electricity scheme presented a competition-free market, resulting in high prices of electricity (Hosoe, 2006).

3.7.2 Relevant policies

Together with the new 2012 FIT program, the Japanese government implemented the electricity system reform policy to reform the monopolized structure of the electricity sector and to spur the deployment of various renewable energy technologies. The reform is focused on three items: 1) establishment of an organization for cross-regional coordination of transmission operators; 2) full retail competition; and 3) unbundle the transmission and distribution sector and full liberalization of retail electricity rates (METI, 2015). The reform is aimed to create a stable electricity supply system by accepting a wide range of energy resources into the grid.

3.8 PV generation in Japan

Following the new FIT program launch in 2012, which aimed to specifically increase the share of PV and wind-generated energy, Japan achieved one of the fastest growth rates of solar PV installations in the world (METI, 2011). Japan has doubled the capacity of renewable energy sources in only three years, with PV generation accounting for most of the new renewable energy resources (REN 21, 2016). Japan recorded 270% increase in the annual growth rate in PV installed capacity during the first half year of 2013 (Friedman, Margolis & Seel, 2016) and became one of the four largest solar PV markets in the world, along with China, Germany and U.S.A. In 2015, Japan recorded the second highest increase solar PV installations, after China, in Asia (Friedman, Margolis & Seel, 2016 & REN 21, 2016). One characteristic of Japan's renewable energy use is its high dependence on solar PV compared to the other markets with large shares of renewable energy use. China, U.S.A and Germany use both wind and solar PV.

3.9 PV generation in the Japanese residential sector

The driving force behind increased use of solar PV in Japan's renewable energy mix is the high volume of PV-generated energy obtained from the residential sector. After the Great East Japan Earthquake in 2011, the country recorded a rapid increase in the share of PV –generated energy within the total energy mix in the residential sector. In 2009, 26% of newly built houses had PV generation systems; in 2014 the number increased to about 50% (Hahn, 2014). While the number of applicants from the non-residential sector requesting installations of PV generation systems under FIT reached 8,899, the number of new applicants from the residential sector was nearly 1.2 million by July 2016 (Agency for Natural Resources and Energy, n.d.). For comparison, more than 1.6 million houses or nearly 6% of all houses in Japan were equipped with the solar PV generation systems by July 2014 (JPEA, 2015).

The unique characteristic of this high number of solar PV generation systems installed in the residential sector was led by various subsidy programs from both the national and local governments. For example, in 2013 the national government subsidized maximum of 199,800 yen for the installation of PV generation system with capacity up to 9.99kW to promote solar PV in the residential sector (JPEA, n.d.) In addition, more than 800 local governments have introduced similar subsidy programs, which allow homeowners to make use of programs simultaneously with the national FIT program. As a result, according to the Agency for Natural Resources and Energy (ANRI), the total generation capacity through installed solar PV generation systems in the residential sector reached 3,618 thousand kW, which makes it the third largest generation capacity in the world (2012). Grid-connected residential PV generation systems have increased since the introduction of the new FIT program in 2012. As of the end of 2013, 3.1GW of energy generated from the residential PV systems had been connected to the grid; and this had increased to 3.8GW by the end of 2014 (Yamazaki, 2015).

3.10 The cost of solar PV panels for the residential sector

The rapid increase in installations of solar PV systems in the residential sector is attributed to the introduction of the new FIT program as well as the decrease in the cost of PV generation systems. In 2012, the average cost of PV generation systems, including installation fees, was 481,000 yen/kW. The cost has been decreasing gradually every year and the cost in 2016 was 354,000 yen/kW (The Purchase Price Calculation Committee, 2016 & Study group for Enhancing Photovoltaic Generation Competition, 2016).

Although the cost has been decreasing over the years, the residential PV systems in Japan remain at a higher cost compared to other countries. Based on the national government data, the cost of residential PV systems in October 2016 was about 354,000 yen/kW, which is 1.8 times higher than the cost in Germany (Study group for Enhancing Photovoltaic Generation Competition, 2016). Figure 1 presents the breakdown of cost associated with residential PV systems in Japan and Germany. According to the figure, the costs of module and power conditioner are the most influential factors that make Japanese residential PV systems to be expensive. Japanese consumers tend to choose high-quality Japanese made components, which are usually more expensive than international makes, is the main contributor for the residential PV systems sold at a higher price (Study group for Enhancing Photovoltaic Generation Competition, 2016).

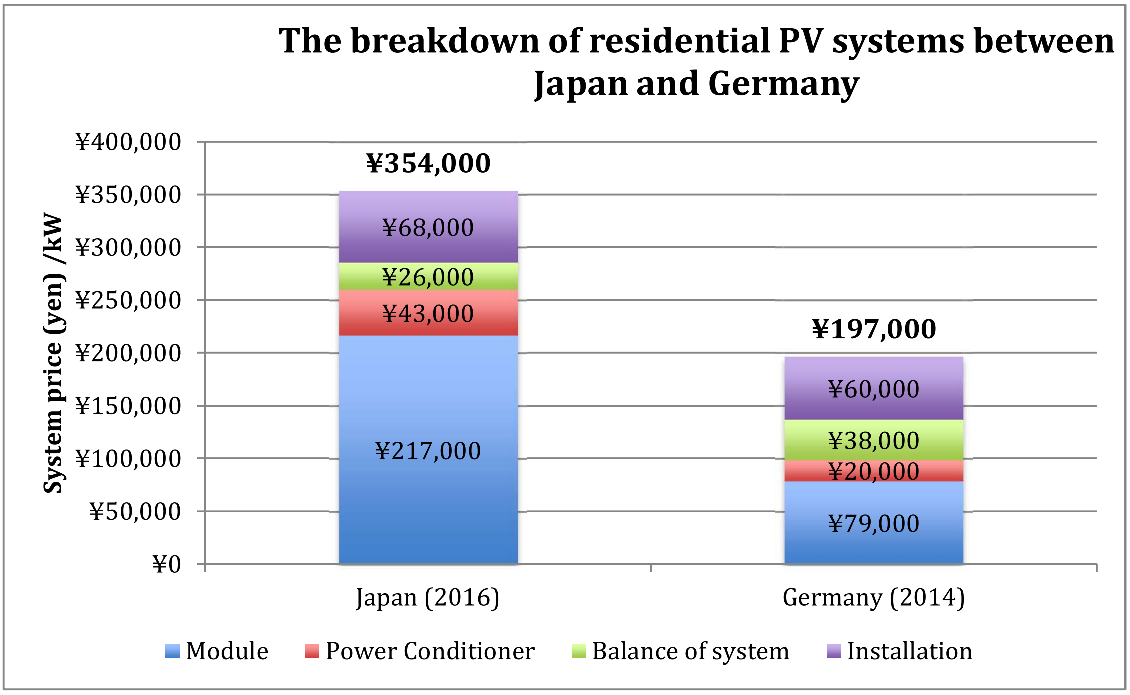


Figure 1: The breakdown of the cost associated with residential PV systems in Japan and Germany
Source: Study group for Enhancing Photovoltaic Generation Competition, the Ministry of Economy, Trade and Industry (METI), 2016

3.11 The 2012 FIT program for the residential PV generation

Through the new FIT program, the government is aiming to encourage residents to reduce electricity consumption; thus, the FIT scheme for the residential sector is designed to allow only trading surplus electricity after initial production is consumed for the household purposes. The FIT program allows homeowners to sell excess electricity to the grid, if they consume less electricity than what they produce at home.

PV generation in the residential sector is restricted in capacity, with a maximum of 10kW rated capacity. In addition, the FIT scheme for PV generation at the residential sector is divided into two categories: (1) single power generation and; (2) double power generation. The difference is that the former only allows selling excess electricity from a PV system only, while the latter allows selling excess electricity from both PV generation and a storage device such as fuel cells, batteries or electric vehicles. Customers can choose their preferred generation category from the two.

3.12 The FIT program for single power generation customers

Table 5 shows purchase prices and guaranteed purchase periods of single power generation. The FIT purchase price first began at the price of 42 yen/kWh in 2012. Since then the price has been reviewed every fiscal year, and in 2016, the purchase price was set at 31yen/kWh. From 2015, houses in the service areas of Hokkaido Electric Power Company, Tohoku Electric Power Corporation, Hokuriku Electric Power Company, The Chugoku Electric Power Company, Shikoku Electric Power

Company, Kyushu Electric Power Company and Okinawa Electric Power Company are mandated to install output control systems due to the limitations on the volume of energy from renewable sources that can be added to the grid of these companies. This allows electric utility companies to limit the output of electricity to 360 hours a year to maintain the grid stability. On the other hand, houses in the service areas of Tokyo Electric Power Company, Chubu Electric Power Company and Kansai Electric Power Company do not require to install output control systems, as these three electric companies still have enough capacity to not restrict PV-generated electricity from the residential sector (Agency for Natural Resources and Energy, 2017).

To compensate for the additional cost associated with the installation of output control devices, the purchase price of solar PV electricity per kWh from houses that have output control equipment is set at 2 yen higher compared to houses that do not have output control devices. In 2015, the purchase price from houses with output control equipment was at 35 yen/kWh; in 2016 the price further decreased to 33 yen/kWh.

Guaranteed purchase period from the residential PV generation systems is 10 years.

Table 5: FIT contract price for single power generation households

Purchase price and year for single power generation households					
	Purchase Price (yen/kWh)				
	2012	2013	2014	2015	2016
When generators are not required to have output control equipment installed	42	38	37	33	31
When generators are required to have output control equipment installed*1				35	33

	Contract period
	10 years

*1: It applies to customers selling electricity to Hokkaido Electric Power Company, Tohoku Electric Power Corporation, Hokuriku Electric Power Company, The Chugoku Electric Power Company, Shikoku Electric Power Company, Kyushu Electric Power Company and Okinawa Electric Power Company

3.13 The FIT program for double power generation customers

Table 6 summarizes the purchase price and applicable purchase year for double power generation households. Similar to the FIT scheme for the single power generation customers, a guaranteed contract period for double power generation customers is 10 years. In 2015, two categories were created: (1) households with output control devices in the service areas of Hokkaido Electric Power Company, Tohoku Electric Power Corporation, Hokuriku Electric Power Company, the Chugoku Electric Power Company, Shikoku Electric Power Company, Kyushu Electric Power Company and Okinawa Electric Power Company and; (2) households without output control devices in the areas of Tokyo Electric Power Company, Chubu Electric Power Company and Kansai Electric Power Company.

The FIT purchase price started at the cost of 34 yen/kW in 2012. Similar to the single power generation category, the price has been reviewed every year. Since 2012, the purchase price has been decreasing gradually and the purchase price in 2016 was 25 yen/kW for houses in Tokyo, Chubu and Kansai areas. For customers that installed output control devices, the purchase price was set at 29 yen/kW in 2015: it further decreased to 27 yen in 2016.

Table 6: FIT contract price for double power generation households

Purchase price and year for double power generation households					
	Purchase Price (yen/kWh)				
	2012	2013	2014	2015	2016
When generators are not required to have output control equipment installed	34	31	30	27	25
When generators are required to have output control equipment installed*1				29	27
	Contract period				
	10 years				

*1: It applies to customers who sell electricity to Hokkaido Electric Power Company, Tohoku Electric Power Corporation, Hokuriku Electric Power Company, The Chugoku Electric Power Company, Shikoku Electric Power Company, Kyushu Electric Power Company and Okinawa Electric Power Company

3.14 Single power generation VS Double power generation

While double power generation has an advantage over single power generation in that double power generation households are able to sell more electricity to the grid by using both PV generation and a storage device, the FIT price for double power generation has been set about 20% lower than that of single power generation for two reasons (Agency for Natural Resources and Energy, 2012). First, double power generation households can sell more electricity than single power generation households that are only equipped with a PV generation system, which create higher economic returns for double power generation customers, if the contract price was the same. To address the issue of unfair gap between single power generation customers and double power generation customers, the purchase price for double power generation households are set at a lower price.

Second, FIT program is designed to promote the widespread use of PV generation in the residential sector to achieve a pervasive share of renewable energy sources in the total energy mix so that it contributes to decrease the amount of electricity produced by fossil-based generations. By having a storage device at home, households can charge the device by using electricity from the grid that are high carbon intensity energy sources, which contradicts with the purpose of FIT. Moreover, household can earn a profit margin by charging up the device during off-peak pricing and sell electricity at a contracted FIT price, which is a higher price than electricity price at off-peak. Such action is against the basic principles of FIT scheme. To prevent such practice, the government set the purchase price for double power generation customers 20% lower price than the purchase price of single power generation customers (Agency for Natural Resources and Energy, 2017).

When households use FIT scheme, they need to choose which generation type they prefer and make a contract with an electric utility company. For houses that have both PV and storage systems but choose single power generation FIT scheme, their integrated PV-storage systems must be wired in a way so that electric discharge from the storage device stops when electricity generated by PV generation is selling to the grid. Households can change generation preferences anytime by making a new contract with the electric company that their homes get serviced.

Compared to the number of applications for single power generation households, the number of applications from double power generation households is much lower. As of July 2016, approximately 80,000 homeowners have registered to use double power generation scheme (Agency for Natural Resources and Energy, n.d.). This number is less than 10% of the total FIT applicants from single power generation customers. While current FIT price for single power generation is economically beneficial, the high cost to install a storage system and uncertainty of investment recovery from the system results in consumers hesitating to either install a storage device or select double power generation.

3.15 The cost of battery storage systems and relevant subsidies in Japan

According to ANRI, the cost of battery storage systems in 2015 was 220,000 yen/kWh; the government aims to further reduce the cost to 90,000 yen/kWh by 2020 (Agency for Natural Resources and Energy, 2016). To support the installation of the systems in the residential sector, various subsidy programs have been introduced by both national and regional governments. The national government initiated a subsidy program in 2012 to promote the use of battery systems in the residential sector. The program compensated 1/3 of the installation cost or maximum of 1 million yen, whichever is less. However, the budget was depleted after a few months each fiscal year and the government terminated the program at the end of 2016 (Matsuki, 2016).

In contrast to the national government subsidy program, various subsidy programs have been offered by regional and local municipalities. Although conditions and an allowance differ by executing agencies, in the fiscal year of (FY) 2016, April 1, 2016 to March 31, 2017, 134 subsidy programs were offered for the residential battery storage systems across the country (Japan Business Publishing Co., Ltd., n.d.). For example, Oyama City in Tochigi Prefecture provided 30,000 yen to homeowners who installed a lithium ion battery storage system. Kamakura City in Kanagawa Prefecture granted 40,000 yen for residential lithium ion made battery storage systems.

3.16 Conclusion

The nuclear power incident by the Great East Japan Earthquake in 2011 triggered a need to reconstruct Japanese energy polices. To compensate for the loss in electricity capacity experienced from shutdown of 54 nuclear power plants post-nuclear power incident in 2011, the Japanese government developed polices to introduce the use of renewable energy sources, mainly PV and wind. Shortly after the earthquake in 2012, new FIT program was introduced. From both economical and environmental perspectives, it was urgent that the government increased the share of electricity from renewable energy sources in a short period of time. As a result, FIT price was set at a higher price, which attracted many residents to install PV systems (Nikkei, 2016).

The residential FIT program is categorized into two groups: single power generation and double power generation. As of July 2016, more than 1.2 million residents have joined to the single power generation FIT program and 80,000 applicants have registered for the double power generation FIT program (Agency for Natural

Resources and Energy, n.d.). From literature review, it has been suggested that current FIT scheme and the price, together with a decrease in the PV system's market price, bring economical benefits to the single power generation scheme or by solely utilizing PV systems. On the other hand, lack of literature on the economic performance of integrated PV-battery systems, uncertainty of investment performance, and the high cost of batteries keep consumers away from either selecting the double power generation FIT scheme or the installation of PV-battery systems for their homes. Moreover, the suspension of national subsidy program for batteries further deteriorated consumer's willingness to buy; for example, in 2015, Sharp Corporation was only able to sell 5,000 battery system units out of 15,000 systems of planned sales (The Sankei Shimbun & Sankei Digital, 2016).

The government has worked to remove barriers to strengthen the residential PV market by introducing polices, such as the introduction of the new FIT program in 2012, especially designed to increase the share of PV, to decrease the cost of PV generation system through subsidy programs. However, policies have not been successful in removing barriers and uncertainties associated with residential PV-battery systems.

Chapter 4: Methodology

4.1 Introduction

This chapter outlines the methodology selected for this research. It describes the sources of information and procedures that are necessary to calculate the economic value of residential integrated PV-battery systems in Japan. The information presented includes: geographical location of the study, study layout and boundaries, descriptions and implications of the data used and key variables. In addition, this chapter describes the data processing procedures and techniques used to estimate NPV and IRR values of integrated PV-battery systems for 36 scenarios.

4.2 Research design

This study was conducted using the *quantitative design approach* (Creswell, 2014); more specifically, *scenario research design* was chosen as the method (Ramirez, Mukherjee, Vezzoli, & Matus, 2015). The study sets out a series of assumptions to test whether PV-battery systems would be a profitable investment, with the NPV value on PV-battery systems being higher than 0, and IRR value of the systems being a higher percentage. This study tests these hypotheses through quantitative analyses. Scenario research aims to investigate if a single variable influences the result of a study (Ramirez, Mukherjee, Vezzoli, & Matus, 2015). The ultimate goal of this research is to determine how the cost and pricing structures impact the overall profitability of PV-battery systems under different conditions.

4.3 Research location

This study analyzes the value proposition of integrated PV-battery systems for two selected single-detached houses located in Kyoto, Japan. The geographical location of this research is shown in Figure 2.

Figure 2: Geographical location of the study
Source: https://wow-j.com/en/Allguides/kyoto/

4.4 Research assumptions

The residential houses used in this study are equipped with neither PV systems nor storage systems. Hypothetical integrated PV-battery systems are assumed. The actual hourly consumption data from these houses are used in the study to calculate self-sufficiency, or the amount of hourly consumption that can be met with the residential supply.

In this research, a value proposition for integrated PV-battery systems will be measured by NPV and IRR. To calculate these values, monetary benefits of the systems are required to be calculated. The monetary benefits will be estimated from the sum of (1) revenue from FIT; and (2) the cost reduction in electricity bills compared to the original power bills, which the study will calculate using the actual electricity consumption data obtained. The research will conduct a case study in Japan; hence, Japanese yen will be used consistently as the monetary unit.

With regard to the study period, referenced from Weniger et al. (2014), Weniger et al. (2014) and Yoza et al. (2014), a 20-year period, March 2017 to February 2037, will be set as a preferred study time.

4.5 Characteristics of the selected dwellings

Two single-detached houses (hereinafter will be referred as House A and House B) will be selected for this study. Table 7 summarizes the characteristics of both houses. In House A, the number of occupants is six, comprised of two adults and four children. A retired couple, a male and a female, live in House B. Both houses are all electronic and are equipped with electrical water heater systems; however, House B also has oil stoves for use in winter.

Figure 3 presents electricity consumption trends of both House A and House B. As it can be seen, monthly electricity consumption of House A is higher than that of House B. The annual electric consumption of House A is 10,209 kWh and its average electricity usage per month is 851 kWh. House B uses an average of 549 kWh of electricity per month and its annual electricity consumption is 6,575 kWh. Compared to average electricity consumption of residents in Japan, at about 5,140 kWh, both House A and House B consume more electricity; indeed, the monthly consumption of House A is nearly double Japanese average electricity consumption. This is due to House A being electronically heated, thus consuming more electricity.

Figure 4, 5, and 6 present monthly electricity consumption by Living time, Day time and Night time, respectively. According to the contracted electricity plan, Living time is set from 7am to 10am and 5pm to 11pm on weekdays and 7am to 11pm on weekends; Day time is set from 10am to 5pm on weekdays; and Night time is set from 11pm to 7am for both weekdays and weekends. Figure 4 presents monthly Living time electricity consumption for both House A and House B. Except for January and February, average electricity consumption for both House A and House B is similar. The difference in January and February may be due to additional electrical heating in House A during Living time.

Figure 5 shows monthly Day time electricity consumption. As it can be seen, the electricity consumption for House B exceeds House A in all months. This difference is attributed to the occupants of House B tending to spend time at the house, while all occupants of House A are out of the house during this time due to work or school. This results in low electricity consumption for House A and high electricity consumption for House B during the Day time.

Figure 6 presents monthly Night time electricity consumption by monthly. Both houses use electricity during Night time for the electrical water heater system, but House A consumes more electricity than House B because House A also relies exclusively on electricity for heating while House B uses both electricity and gas for heating.

Figure 7 presents electricity consumption by season: summer and winter. In this graph electricity consumption from March to August is categorized as summer and electricity consumption from September to February is categorized as winter. As it can be seen, both House A and House B record higher electricity consumption in winter months. This is caused by the usage of electric heaters to heat the houses.

As it can be seen in Figure 8, average hourly electricity consumption, House A consumes a higher amount of electricity at night. The use of the electrical water heater system during the night is the biggest contributor for the higher electricity consumption at night. Since every occupant is out of the house for work or school in the daytime, except weekends and holidays, electricity consumption during the day is low. Compared to House A, the load profile of House B shows relatively consistent usage of electricity throughout the day; yet, similar to House A, due to the usage of the electric water heating system, the overall electricity consumption profile indicates a higher volume of electricity consumed at night than in other periods of the day.

Figure 9 presents hourly electricity consumption for both weekdays and weekends. As mentioned earlier, all the occupants in House A are out of the house during weekdays, hence lower electricity consumption is recorded during daytime. Yet, its electricity consumption in weekends records lower electricity consumption than consumption in weekdays. House B also shows lower electricity consumption on weekends than during weekdays. This could be due to various reasons; however, this study does not have information to identify the cause of this trend.

Table 7: Characteristics of House A and House B

	House A	House B
Type of a house	Single-detached house	Single-detached house
Number of occupants	6 (2 adults and 4 children)	2 (2 adults)
Characteristics of electricity usage	• Equipped with an electrical water heater system • Fully dependent on electricity for heating	• Equipped with an electrical water heater system • Electricity plus oil stoves

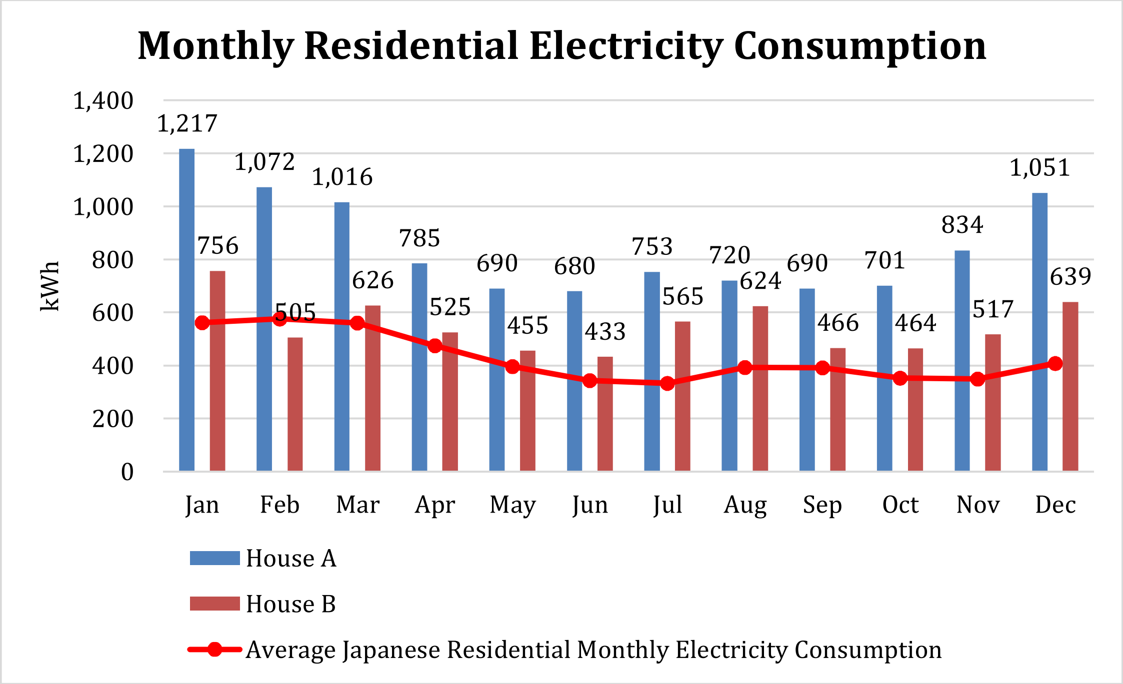


Figure 3: Monthly residential electricity consumption
Note: House A: January 1, 2015 – December 31, 2016, House B: December 24, 2015 – December 23, 2016

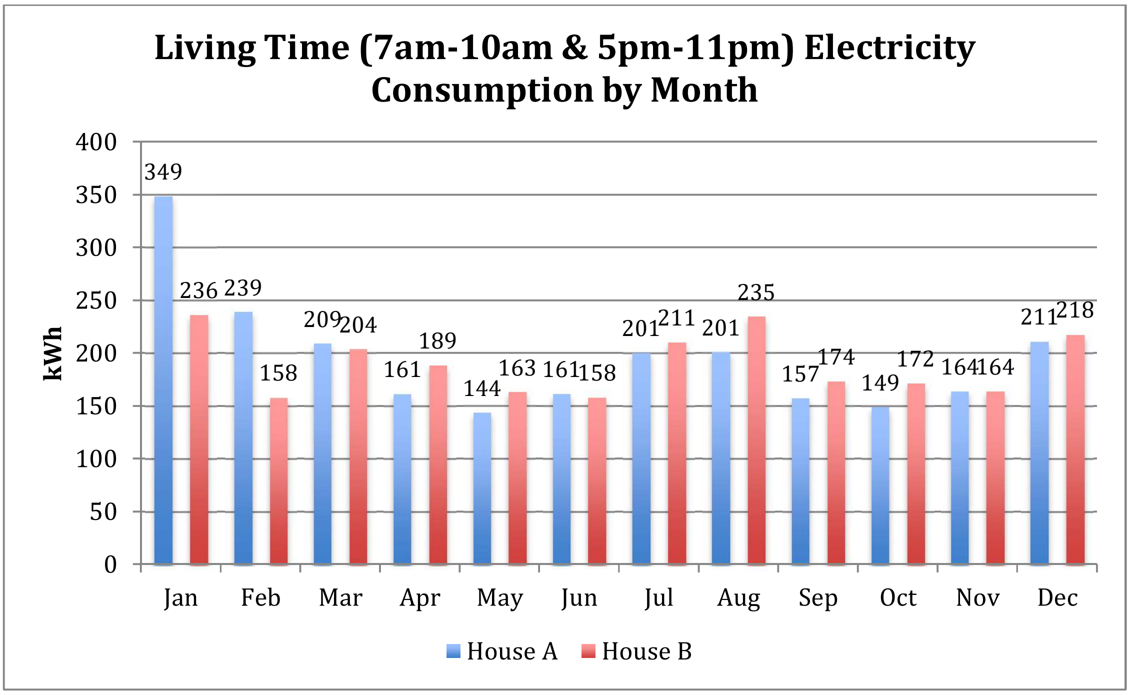


Figure 4: Living time electricity consumption by month
Note: House A: January 1, 2015 – December 31, 2016, House B: December 24, 2015 – December 23, 2016

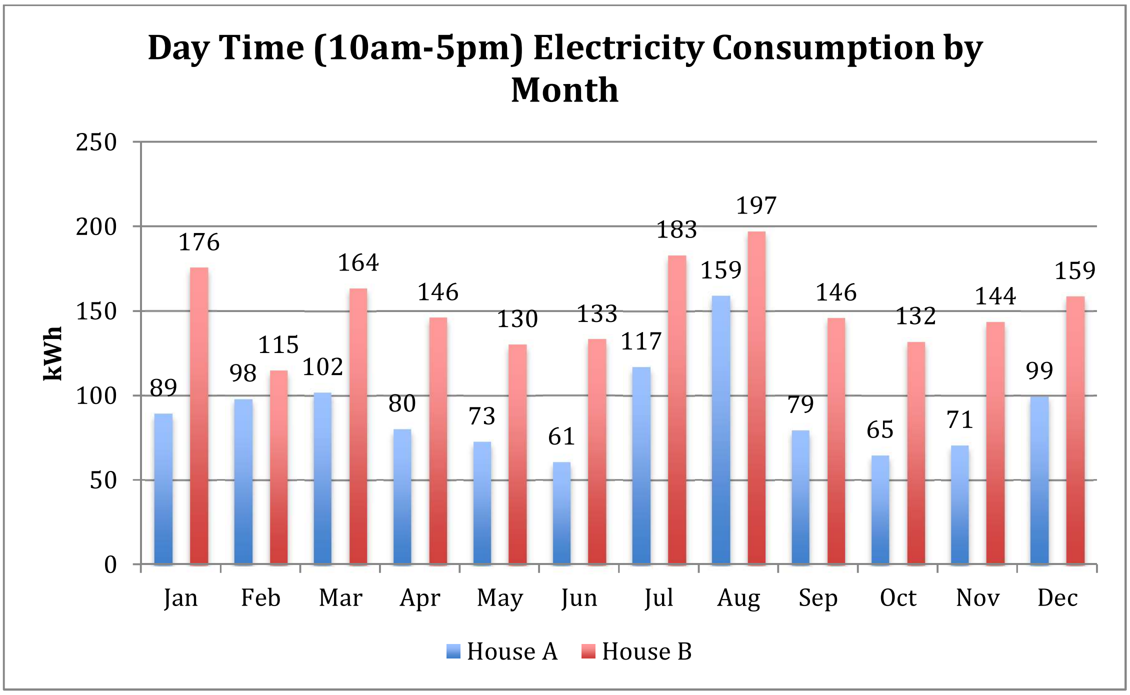


Figure 5: Day time electricity consumption by month
Note: House A: January 1, 2015 – December 31, 2016, House B: December 24, 2015 – December 23, 2016

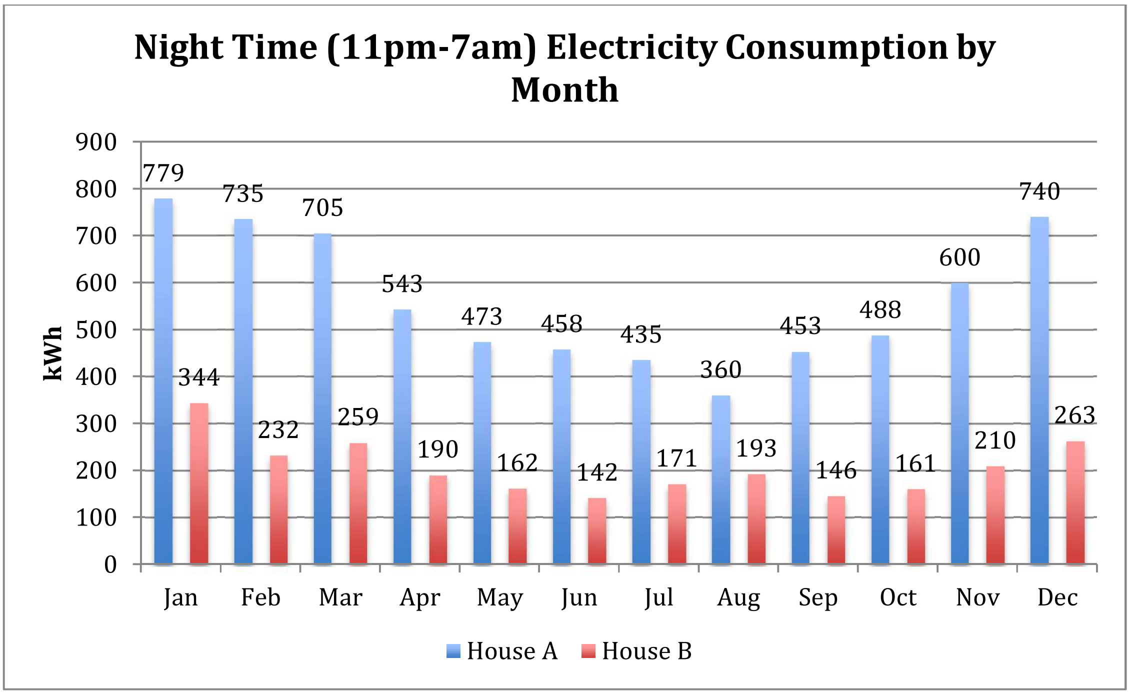


Figure 6: Night time electricity consumption by month
Note: House A: January 1, 2015 – December 31, 2016, House B: December 24, 2015 – December 23, 2016

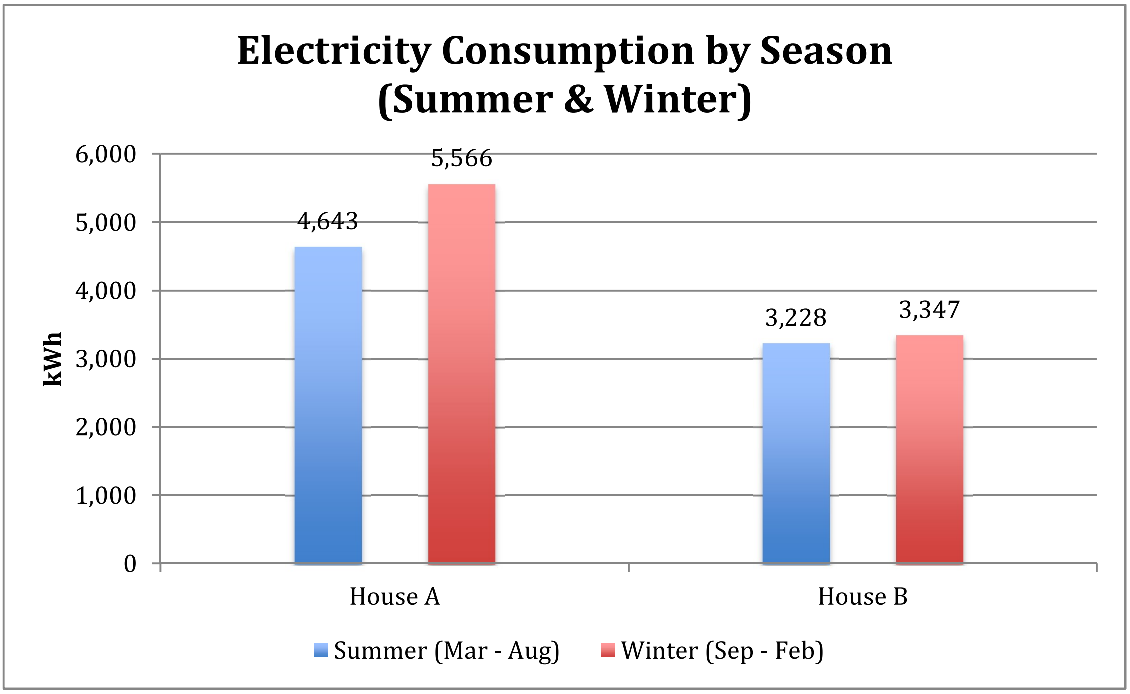


Figure 7: Electricity consumption by season (summer and winter)
Note: House A: January 1, 2015 – December 31, 2016, House B: December 24, 2015 – December 23, 2016

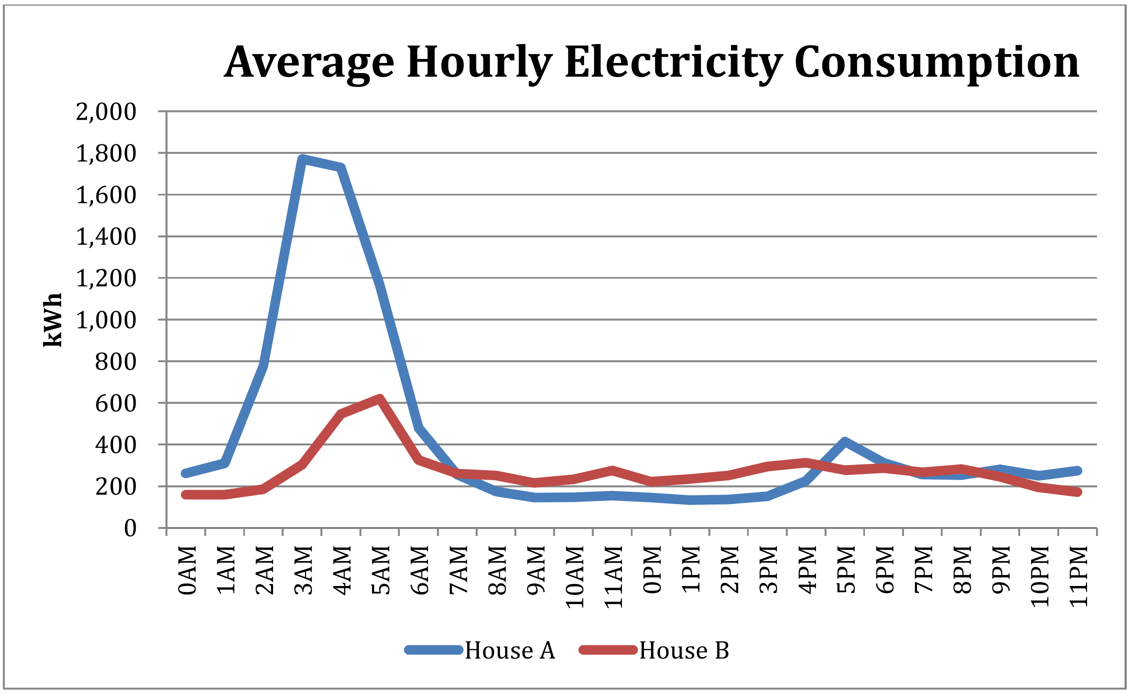


Figure 8: Average hourly electricity consumption of House A and House B
Note: House A: January 1, 2015 – December 31, 2016, House B: December 24, 2015 – December 23, 2016

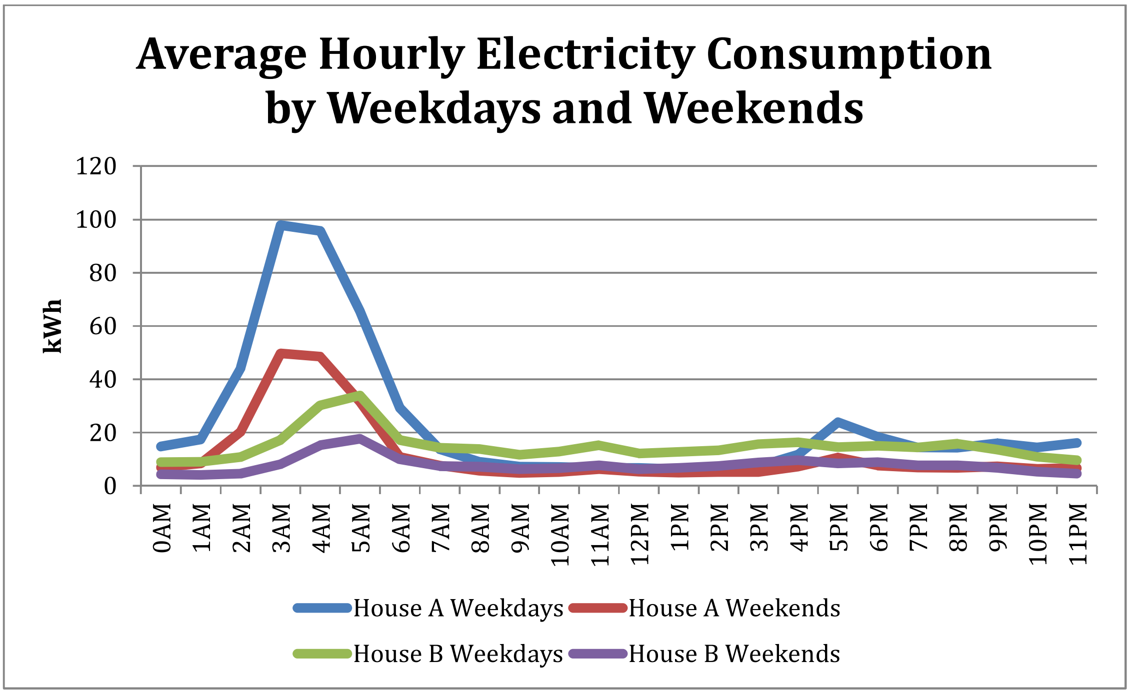


Figure 9: Hourly electricity consumption by weekdays and weekends
Note: House A: January 1, 2015 – December 31, 2016, House B: December 24, 2015 – December 23, 2016

4.6 Study layout and boundaries

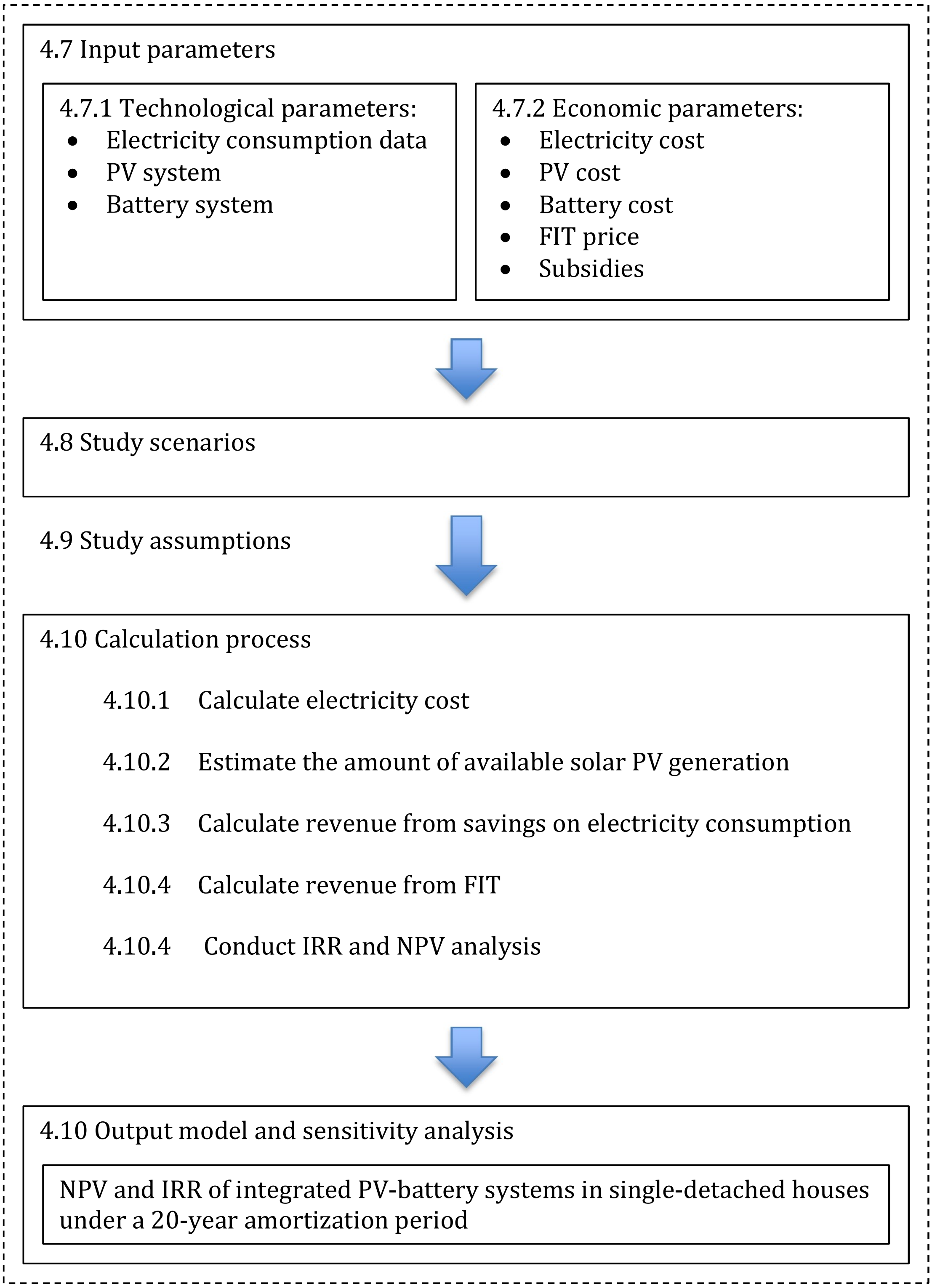


Figure 10: Model structure overview
Source: Author

Figure 10 presents the study layout and boundaries of this research. This research will use NPV and IRR as indicators to measure the value proposition of integrated PV-battery systems at single-detached houses in Japan. In order to conduct numerical analysis, input parameters will be set. In this study, the input parameters will consist of two categories: (1) technological parameters and; (2) economical parameters. In each parameter, specific items will be estimated, which will be identified either by available information or assumptions. This research will use *Microsoft Excel* in the analysis processes. Five calculation steps will be conducted to analyze NPV and IRR of integrated PV-battery systems in single-detached houses under a 20-year investment period. As a concluding step, a sensitivity analysis will be conducted over input parameters and the cost of battery storage systems, to determine its impacts to the output parameters, NPV and IRR. The parameters and calculation processes are described in the next sections.

4.7 Input parameters

Input parameter for this research will be classified into two main categories: (1) technological parameters; and (2) economical parameters. Each category of parameter will hold key information to this study.

4.7.1 Technological parameters

Three technological parameters will be used in this research: (1) electricity consumption data; (2) PV system; and (3) battery system.

4.7.1.1 Electricity consumption data

In this research, actual electricity consumption data from House A and House B will be used. Both houses are equipped with a smart meter, which records electricity consumption at 30 minute intervals. The original data from House A included the electricity consumption from December 16, 2014 to January 18, 2017; House B recorded the electricity consumption amounts from December 24, 2015 to December 26, 2016 in order to perform analysis based on full calendar year, this study will use the electricity consumption data of House A from January 1, 2015 to December 31, 2016 and data for House B from December 24, 2015 to December 23, 2016.

In this research, it will be assumed that electric load profile of each house will remain unchanged throughout the 20-year study period.

4.7.1.2 PV system

Since the selected houses are not equipped with PV systems, the study will assume that systems are installed at both houses. Assumed data on PV capacity and solar intensity are required to estimate the expected electricity generation from the systems.

- PV capacity

This study will apply PV capacity of 4.48 kW to both houses. This assumption is based on a reference from JPEA, a non-profit organization responsible for collecting data on the average solar PV system installed at residential homes in each prefecture in Japan. According to the latest available data from JPEA, the average PV capacity that was installed at 1,229 existing houses in Kyoto Prefecture over the period of April 2014 to February 2015 is 4.48 kW.

- Solar intensity

In order to calculate expected electricity generation amount from a 4.48 kW PV system, the information on solar intensity is critical. This study will use a meteorological online database called *MONthly mean SOLAr radiation data* (MONSOLA-11) and *MEteorological Test data for PhotoVoltaic system* (METPV-11) created by NEDO to determine the intensity of solar radiation. MONSOLA-11 and METPV-11 are the latest versions, which were updated in 2015. Their data is composed of the average data tabulated through meteorological weather stations or *Automated Meteorological Data Acquisition System* placed in 831 locations all over Japan from the period of 1981 – 2009 and 1990 – 2009, respectively.

In this research, MONSOLA-11 and METPV-11 data from Kyoto City will be applied. The data will be retrieved from the latitude of 35° 0.9' N, the longitude of 135° 43.9' E and the altitude of 41 meters.

To identify the intensity of solar radiation in Kyoto City, MONSOLA-11 will be used to first determine an appropriate tilt angle of PV panels in the Kyoto area. Figure 11 shows the optimal tilt angles of PV panels by monthly, yearly and seasons in the

Kyoto area. This study will assume that a PV system is a fixed angle type; thus, yearly optimal tilt angle, 28.7 degrees (°), is referenced. Since METPV-11 only allows to retrieved the data at the tilt angle of 29°, and hence the study will apply an optimal angle of 29°.

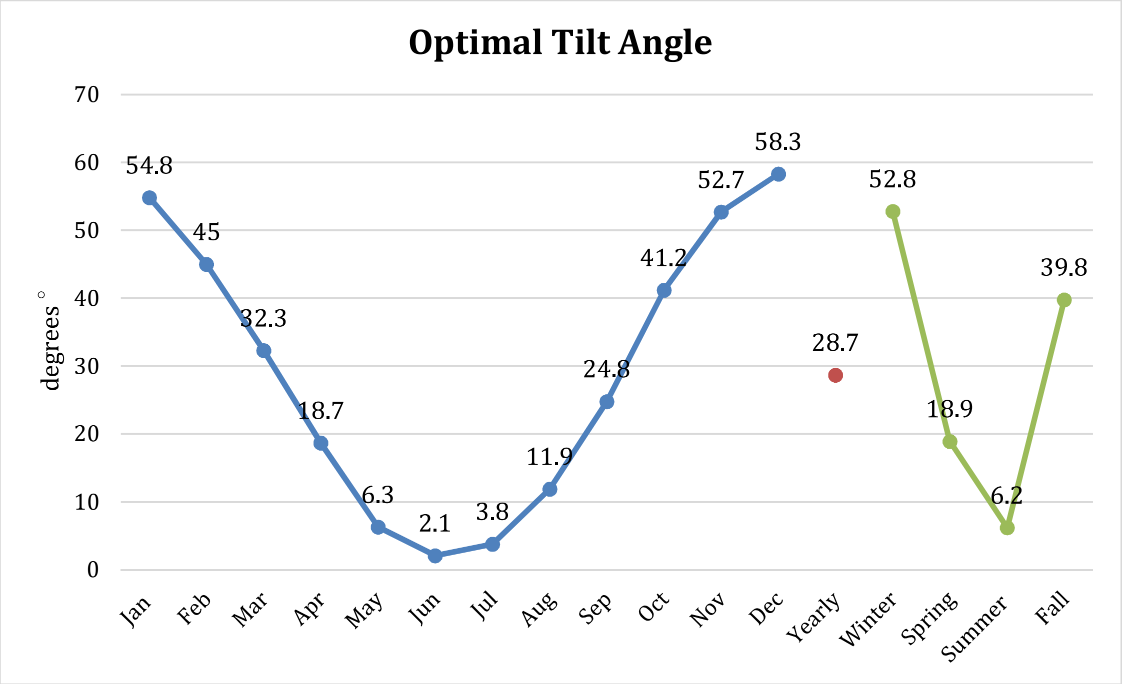


Figure 11: Optimal tilt angle
Source: MONSOLA 11 from NEDO

Tilt angle depends on the availability of roof angle. Table 8 presents the relationship between tilt angle and the amount of solar radiation available in Kyoto, Japan. As it can be seen, the difference in the amount of solar radiation between 29° and 0° tilt angles are about 8.5%. Yet, since the angle of the roof for both House A and House B are unknown, the study will assume that both houses have 30° of roof angle.

Table 8: Tilt angle and amount of solar radiation

Angle	Amount of solar radiation (yearly average)
29°	3.74 kWh/ m^2
20°	3.71 kWh/ m^2
10°	3.61 kWh/ m^2
0°	3.42 kWh/ m^2

Source: METPV-11 from NEDO

Once the optimal fixed tilt angle is determined, the study will use METPV-11 to retrieve data on the amount of solar radiation available and the duration of available sunlight at the assumed tilt angle. Since METPV-11 only allows to retrieve the data at the tilt angle of 29°, the study will set an optimal tilt angle of 29°. To yield maximum solar output, it will be assumed that the systems face south and have no shading.

Solar radiation data at the designated tilt angle is required to estimate expected generation amount. METPV-11also provides hourly solar radiation data throughout the year at 29° tilt angle face south in the unit of MJ/m^2. Since the study will use kWh, the unit will be converted into kWh. To convert the unit from MJ/m^2 to kWh/m^2, the following equation will be used:

$$1\mathrm{MJ}/m^2 = 0.2777778\ kWh/m^2 \qquad (1)$$

- PV outputs

This study will reference and modify the equation presented by NEDO to calculate expected hourly PV generation amount. The original equation used by NEDO to calculate annual PV generation is given below.

$$Ep\ (kWh/yr) = H(kWh/m^2/day) \times K(\%) \times P(\text{kW}) \times 365 \div 1(kW/m^2) \qquad (2)$$

where, *Ep* is expected annual generation amount (kWh/year); H is the amount of the intensity of solar radiation (kWh/m^2/day); K is a performance ratio and coefficient for losses. P is the capacity of a PV system, 365 as the number of days per year and 1 is an average solar irradiance (kW/m^2). The NEDO equation specifies K value as 0.73 or 73%. Table 9 provides the detail information on the description of K value.

Table 9: Descriptions of K value

Items	**Percentages (approximately)**
Temperature losses	15%
Invertor losses	8%
Cable losses, losses due to dust, snow, etc.	7%

Source: NEDO, n.d.

Since hourly intensity solar radiation data can be retrieved from METPV-11, the study will modify Equation 2 to the following equation to calculate hourly PV generation *Ep*

$$Ep = H \times K \times P \div 1\ [kWh/hour] \qquad (3)$$

where, *Ep* is expected hourly generation amount, *H* is the data from METPV-11, K is the performance ratio (73%) and *P* is the selected PV capacity (for this study, 4.48 kW).

Degradation factor is also one of the important factors. In this study, degradation factor will be set at 0.5%/year. The Fisheries Agency under the Ministry of Agriculture, Forestry and Fisheries in Japan recommends the use of 0.5%/year degradation factor when estimating PV generation (n.d.). Moreover, from technological performance analyses of the PV systems at *Tsubozaka-dera* in Nara

Prefecture, which are one of the longest operating PV generation systems in Japan, it was found that the systems recorded 6.43% degradation after 28 years of the operation or equivalent to about 0.23%/year degradation rate (The Sankei Shimbun & SANKEI DIGITAL, 2016 and Kaneko, 2014). Thus, 0.5%/year degradation factor is a conservative factor allowing a margin for reduced performance.

Under 0.5%/year degradation scenario, a performance ratio in the twentieth investment year is expected to be 90.5% compared to the first investment year. Since the study will assume that no degradation will occur in the first investment year, two types of equation will be used to calculate expected PV generation. Equation 3 will be used to calculate expected PV generation during the first year and Equation 4 will be used to estimate PV generation from the second to the twentieth year EP_{2-20}

$$Ep_{2-20} = H \times K \times P \div 1 \times \{100 - (\mathcal{Y} - 1) \times 0.5)\}\ [kWh/hour] \tag{4}$$

where, H is the data from METPV-11, K is the performance ration (73%), P is the selected PV capacity (for this study, 4.48 kW), and $\mathcal{Y}$ is years since installation.

Degradation may occur in other components of PV systems due to age and climate conditions, though it is challenging to identify these factors. Therefore, this study will not incorporate any other degradation factors except for the age-related degradation factor for PV panels.

Figure 12 presents the amount of monthly PV generation by 4.48kW PV systems. During the study time, it is expected that the PV systems will generate the most electricity in August, which is 450.3kWh. PV generation amount in November and December are expected to be the lowest in the year. The system is expected to generate 4,417kWh electricity annually on average during the study period. Figure 13 describes the amount of hourly generation by the selected PV capacity (for this study, 4.48 kW) in average of 20 years. As it can be seen, PV starts to generate electricity from 6am until 7pm. It hits the maximum generation amount at noon, at 20.6kWh.

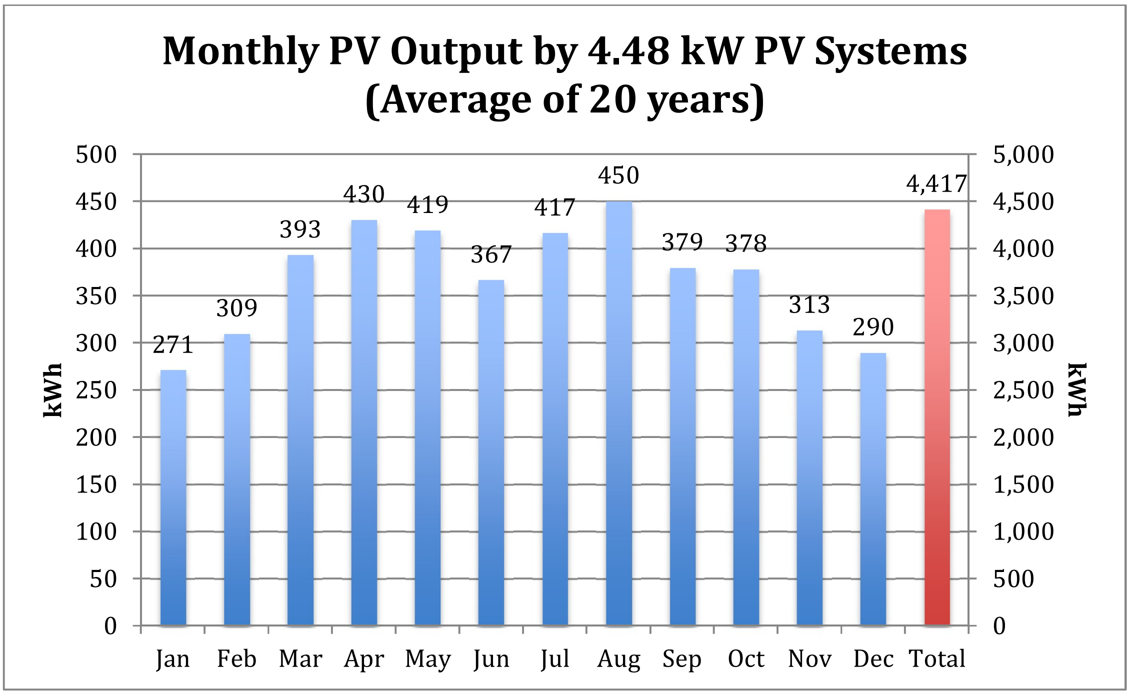


Figure 12: Monthly PV output by 4.48kW PV systems

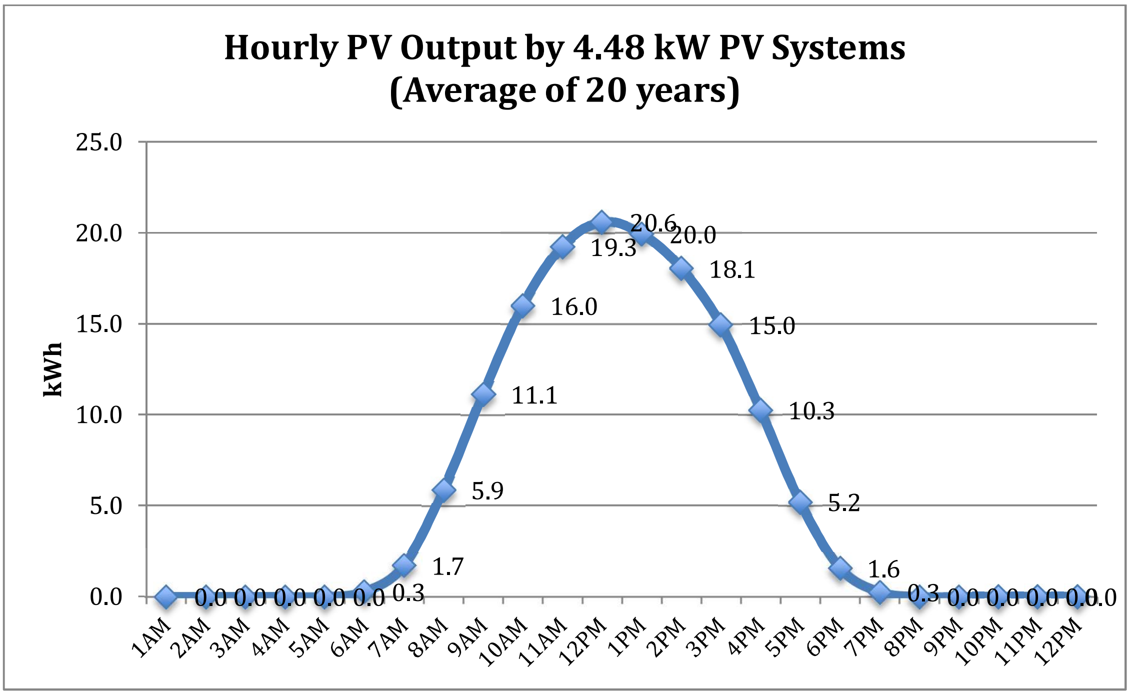


Figure 13: Hourly PV output by 4.48kW PV systems

4.7.1.3 Battery system

➢ Selected battery capacity and its technological performance profiles

From available online data, this research will assume that the selected houses installed a Kyocera 7.2kWh lithium ion battery system. Table 10 summarizes the details of the selected battery system for this study.

Table 10: Descriptions of a lithium ion battery system

Battery manufacture	Kyocera
Type	EGS-LM72BIII
Battery designed capacity	7.2 kWh
Depth of discharge (DOD)	80%
Efficiency of invertor (EI)	94%
Charging and discharging efficiency (CE)	95%
Total energy efficiency ($\mathcal{X}$)	80%
Usable storage capacity ($\mathcal{Y}$)	5.14 kWh at DOD80% 3.85 kWh at DOD60% 2.57 kWh at DOD40%

Required electricity to recharge ($\mathcal{Z}$)	6.45 kWh at DOD 80% 4.84 kWh at DOD60% 3.23 kWh at DOD40%
Charging time	2.5 hours

Source: KYOCERA Corporation, n.d.

While, the battery's designed capacity, allowable maximum DOD, and the efficiency rate of invertor are reported in the product's performance profiles, total energy efficiency, charging and discharging efficiency, usable battery capacity, and required electricity amount to recharge the battery will be calculated using the following equations.

- Total energy efficiency and charging and discharging efficiency

  Total energy efficiency $\mathcal{X}$ can be explained by the equation:

  $$\mathcal{X} = CE \times EI \times DE \times EI\ [\%] \tag{5}$$

  where, $\mathcal{X}$ is total energy efficiency, CE is charging efficiency, EI is the efficiency of an invertor, and DE is discharging efficiency.

  This research will assume that the total energy efficiency of the selected battery will be 80%. According to Arai et al. (2004), total energy efficiency of 10kW battery storage systems is around 74 – 75%. Hashimoto et al. (2015) identified that 20MWh storage battery systems recorded 86.2% total energy efficiency. Kaneko presented a case that 300MWh battery systems recorded more than 70% total energy efficiency (2016). The 80% total energy efficiency rate will be selected as being within the range cited from the above references.

Since the efficiency of the invertor is known and the targeted total energy efficiency will be set for the study, charging and discharging efficiency will be calculated as 95%.

- Usable storage capacity

  Usable storage capacity $\mathcal{Y}$ will be calculated from equation:

  $$\mathcal{Y} = (BDC \times \mathcal{X}) \times DE \times EI \ [kWh] \quad (6)$$

  where, *BDC is* the battery's designed capacity (7.2 kWh), $\mathcal{X}$ is DOD, *DE* is discharging efficiency (95%), and *EI* is the efficiency of an invertor (94%).

- Amount of electricity required to recharge the battery

  To calculate the amount of electricity required to fully recharge the battery $\mathcal{Z}$, below equation will be used.

  $$\mathcal{Z} = (BDC \times \mathcal{X}) \div (CE \times EI) \ [kWh] \quad (7)$$

  where, *BDC is* the battery's designed capacity (7.2 kWh), $\mathcal{X}$ is DOD, *CE* is charging efficiency (95%), and *EI* is the efficiency of an invertor (94%).

While the maximum DOD of the selected battery is restricted at 80%, they could operate at any lower DOD levels. Therefore, this study will assume that the battery operates at three different DOD: 80%, 60%, and 40%.

Using Equation 6, maximum operational capacities at DOD 80%, 60%, and DOD40% will be calculated as 5.14 kWh, 3.85 kWh and 2.57 kWh, respectively. Based on

Equation 7, the amount of electricity required to recharge DOD 80%, 60%, and 40% will be set as 6.45 kWh, 4.84 kWh, and 3.23 kWh, respectively.

With regards to the degradation of a battery, since there is currently no international standard to measure degradation, it is difficult to set degradation factors; thus, the study will not incorporate any other factors except for the number of life cycles.

4.7.2 Economic parameters

Five economic parameters will be used in this study: electricity cost, PV cost, battery cost, FIT price and subsidy. The next sections describe each parameter in detail.

4.7.2.1 Electricity cost

Electricity cost is one of the important parameters for this study, because the study will calculate the monetary benefits of PV-battery systems from the cost reduction in electricity bills compared to the cost of original electricity bills. It will be assume that electricity cost changes every year throughout the investment period.

- Base electricity costs

In order to calculate the cost of electricity of House A and House B, information on contracted electricity rates is necessary. Table 11 summarizes contracted electricity charges of both House A and House B. Both houses are contracted with the same electric plan, *happy e time*, service provided by the Kansai Electric Power Company

(KEPCO). Their contracted electricity prices consist of two main categories, which are electricity price from October 1 to June 30 and the price from July 1 to September 30. In both categories, three sub-categories are set for weekdays (Monday to Friday): Living time, Day time, and Night time; and two sub-categories are set for weekends (Saturday, Sunday, public holidays and January 2, January 3, April 30, May 1, May 2, December 30, and December 31): Living time and Night time. Different electricity prices are applied for each time-of-use category. Due to an increase in the peak demand of electricity in the summer, the Day time electricity price from July 1 - September 30 is set higher than the price set for the same time period from October 1 to June 30 (The Kansai Electric Power Company, n.d.).

In this research, electricity cost will refer solely to electricity consumption rates. Other factors such as, renewable energy surcharges, power costs for supplier and various discount incentives will not be included.

Table 11: Time-of-use electricity prices, 2016

<table>
<tr><th colspan="4">From October 1 - June 30</th></tr>
<tr><th>Weekday
(Mon - Fri)</th><th>yen/kWh</th><th>Weekend
(Sat, Sun & Holidays)</th><th>yen/kWh</th></tr>
<tr><td>Living time
(7am - 9:59am & 5pm - 10:59pm)</td><td>27.32</td><td>Living time
(7am - 10:59pm)</td><td>27.32</td></tr>
<tr><td>Day time
(10am - 4:59pm)</td><td>35.54</td><td>Night time
(11pm - 6:59am)</td><td>13.10</td></tr>
<tr><td>Night time
(11pm - 6:59am)</td><td>13.10</td><td></td><td></td></tr>
<tr><th colspan="4">From July 1 - September 30</th></tr>
<tr><th>Weekday
(Mon - Fri)</th><th>yen/kWh</th><th>Weekend
(Sat, Sun & Holidays)</th><th>yen/kWh</th></tr>
<tr><td>Living time</td><td>27.32</td><td>Living time</td><td>27.32</td></tr>
</table>

(7am - 9:59am & 5pm - 10:59pm)		(7am - 10:59pm)	
Day time (10am - 4:59pm)	38.89	Night time (11pm - 6:59am)	13.10
Night time (11pm - 6:59am)	13.10		

Source: The Kansai Electric Power Company, 2016

- Future electricity costs

Although it is uncertain for the study to predict the future residential electricity costs, the study will apply three different scenarios based on the past trend of residential electricity prices in Japan.

  - *Scenario 1 (EPS1): electricity price does not change over the study period*
  - *Scenario 2 (EPS2): electricity price increases 1.31 %/year based on Table 11*
  - *Scenario 3 (EPS3): electricity price increases 3.62 %/year based on Table 11*

Figure 14 shows average residential electricity price in Japan from 1995 to 2015. As of 2015, the average residential electricity price is 24.2 yen/kWh. EPS2 will be set based on the average annual change in electricity price during the 1995 - 2015 period.

As a result of the Great East Japan Earthquake in 2011, the Japanese energy mix has changed drastically and the residential electricity price increased. EPS3 will be selected based on the average annual change in electricity price during the 2011 – 2015 period.

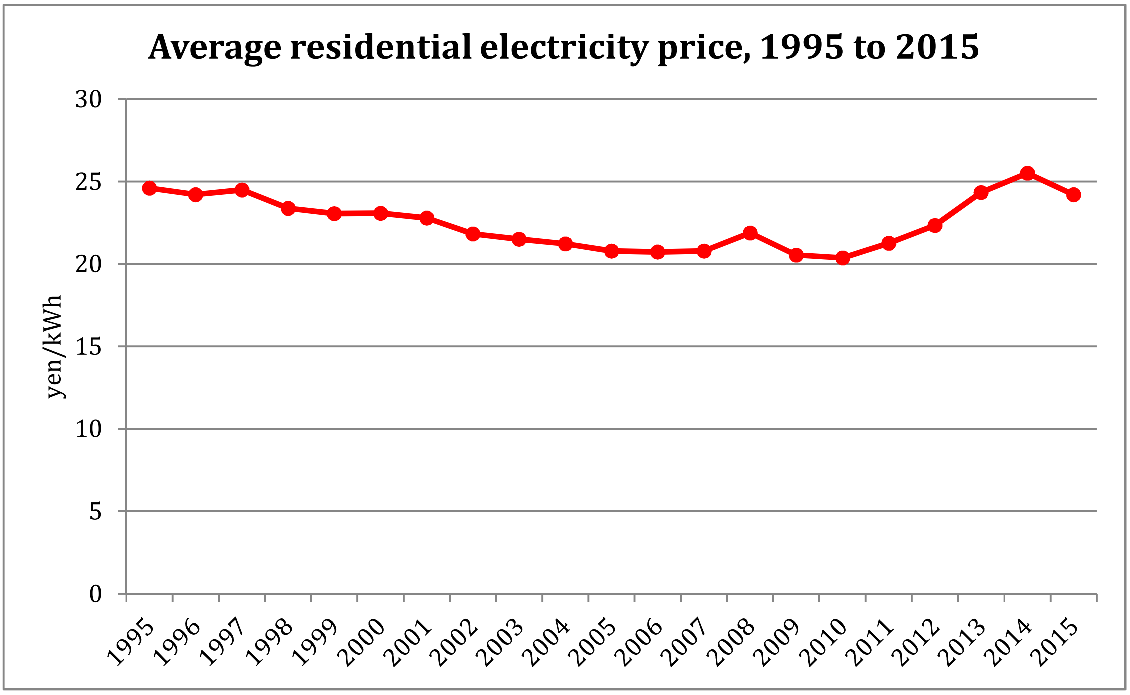


Figure 14: Average residential electricity price in Japan from 1995 to 2015
Source: The Federation of Electric Power Companies of Japan (FEPC), n.d.

4.7.2.2 PV cost

In this study, the cost of PV systems will consist of two types of costs: (1) installation costs; and (2) maintenance costs. Both costs will be estimated using a government source.

- Installation costs

As described earlier in section 3.10, METI reported that the average PV systems cost, including installation cost, for the period of July to September 2016 was 354,000 yen/kW. Therefore, the installation cost of a PV system P_{inst} will be calculated using the following equation:

$$P_{inst} = P_{cap} \times C \; [yen] \tag{8}$$

where, P_{cap} is the PV capacity (4.48 kW), and C is the cost of PV systems cost per kW (354,000 yen/kWh).

- Maintenance costs

Two types of maintenance costs will be incorporated in this research, which are: (1) periodic inspection cost; and (2) cost to replace a power conditioner. Table 12 summarizes the details of the maintenance costs. According to a report by the Purchase Price Calculation Committee under METI, periodic inspection is required every 4 years and a power conditioner is required to be replaced within twenty years after the installation of a battery system due to degradations (2016). Based on available information from the web, the study assumes that the replacement of a power conditioner will take place after 10 years from the installation (Solxsell, 2016). With regard to the costs, periodic inspection costs 20,000 yen/inspection and replacing a power conditioner costs 200,000 yen (METI, 2016). In this study, these two costs will be included as running cost items.

Table 12: Descriptions of maintenance costs

Cost items	Cost (yen)	Time
Periodic inspection	20,000	Every four years
Power conditioner	200,000	After 10 years

4.7.2.3 Battery cost

Similar to PV costs, two criteria will be used to assume as battery costs: installation costs and maintenance costs.

- Installation costs

From available online data, the study estimates the cost of battery as 1,417,000 yen or 197,000 yen/kWh including installation (Zero Home Corporation, n.d.).

- Maintenance costs

The manufacturer of the selected battery guarantees the system for the first 10 years after the installation. Therefore, it will be assumed that no expense occurs for maintenance during the first ten years. From the 11th year to 20th year, since it is difficult to obtain actual maintenance costs, the study will assume that the maintenance costs will be 1.5% of the battery investment costs, which is based on the study by Naumann et al. (2015) and Weniger et al. (2014).

Information on expected life expectancy of the selected battery is available from the manufacturer's brochure, which is 6,000 cycles at DOD of 80%. This study will assume that battery is used one cycle every day; therefore, 6,000 cycles is equivalent to 16 years. In the case of DOD 80%, the study will assume that a new battery is installed in the 17th year. According to METI, the Japanese government aims to reduce the cost of batteries to 90,000 yen/kWh by 2020 (2017). Thus, this research will incorporate this cost as a benchmark and will assume that the cost to re-install the same size of battery system in 2033 will be 648,000 yen including an installation cost (90,000 yen/kWh × 7.2 kWh). As described in 4.6.1.3, the study will also consider the battery to operate at different DOD, which are DOD 60% and DOD40%. As presented by Omar et al. (2014), operating a battery at a low DOD can contribute to increasing the life cycle of the battery. Omar et al. (2014) studied the relationship between DOD and the number of life cycles of a battery. Figure 15 shows the relationship between the number of life cycles and DOD of the selected battery for this study. This was developed by identifying the rate of change of the number of life cycles at different DOD from Omar et al. (2014) and applied same rate of change to the battery for this study. According to Figure 15, the battery can use up to 46,117 cycles at DOD 40% and 23,120 cycles at DOD 60%. Assuming that a battery is used one cycle every day, the life expectancy of a battery when DOD 60% is 63 years and DOD 40% is 126 years. Therefore, it will be assumed that there will be no need to re-install butteries under DOD 40% and DOD60%; yet the maintenance costs of 21,000 yen or 1.5% of the battery investment will be included throughout the study period.

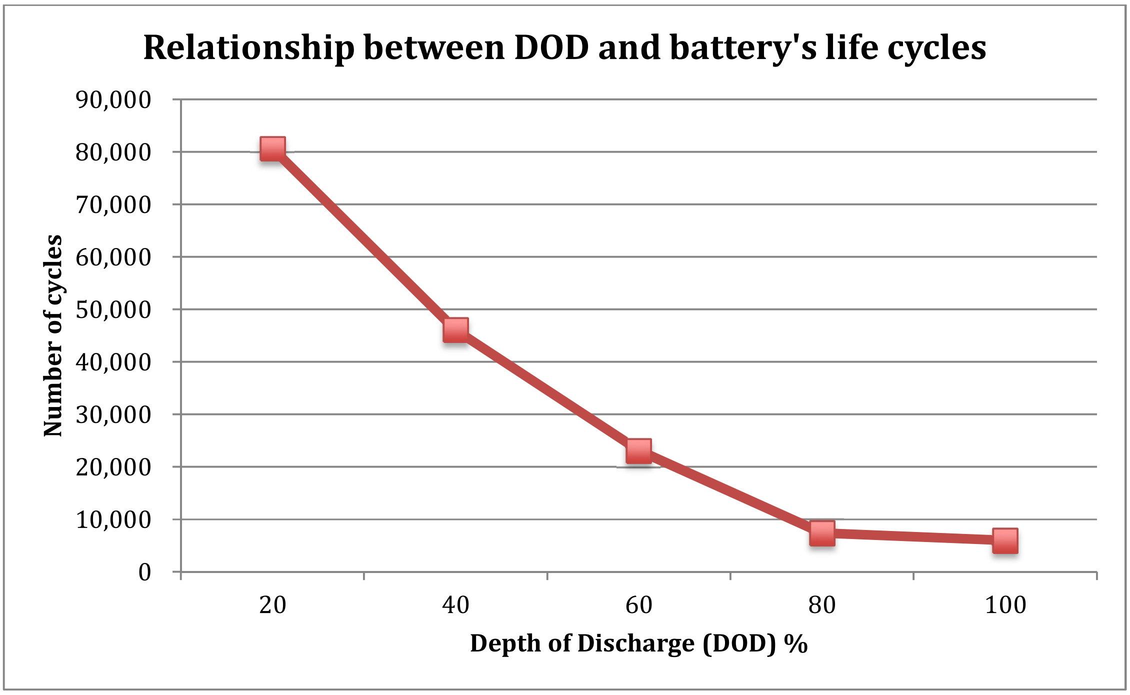


Figure 15: The relationship between DOD and battery's life cycles

4.7.2.4 FIT price

- FIT price from 1st to 10th year

As described earlier in Chapter 3, FIT for the current Japanese residential sector has two FIT categories, which are single power generation and double power generation. They both guarantee to purchase excess amount of electricity from residents at the contracted price for 10 years.

This study will use scenarios for both of the FIT types. As of March 2017, FIT price for single power generation in Kyoto area is 31 yen/kWh and double power generation is 25 yen/kWh. Therefore, the study will use these FIT prices for the first ten years of the study period.

- FIT price from 11th to 20th year

Unlike FIT price for the first ten years of the study time, FIT price for the second part of the investment period is unknown. Thus, the study will assume a FIT price from Year 11 to Year 20. This study will assume that from the 11th year there will not be differentiation between single power generation and double power generation. From the past trend of decrease in FIT contract price in the Japanese residential sector, it can be expected that the FIT price will be lower in the future. Based on such trends, this research will assume two different FIT price scenarios:

  - *Low price scenario (LPS): 9.4 yen/kWh*
  - *High price scenario (HPS): 14.5 yen/kWh*

The cost for lower price scenario is based on the average electricity price traded during peak time at Japan Electric Power Exchange in 2016. The high price scenario is based on the projected residential PV generation cost per kWh in 2030 reported by KEPCO (2017). By using two different price scenarios, the study will aim to present multiple outcomes to estimate the economic impact of PV-battery systems under a variety of conditions.

4.7.2.5 Subsidies

In FY 2016, Kyoto City provided subsides for residents whom newly installed PV and/or battery storage systems. For single-detached house owners, the city provided 20,000 yen/kW up to 4 kW capacity for PV systems; and granted 50,000 yen/kWh up to 6 kWh capacity for battery storage systems. The subsidized amount increased if households install both PV and storage systems at the same time. In such case, the city provided 40,000 yen/kW up to 4 kW for PV systems; and 100,000 yen/kWh up to 6 kWh for battery storage systems. In this study, it will be assumed that both House A and House B received 760,000 yen subsidy from the government for installing integrated PV-battery storage systems.

4.8 Study scenarios

Based on the above criteria, this research will conduct NPV and IRR calculation of PV-battery systems under 36 different scenarios for both House A and House B. Table 13 lists the details of each scenario.

Table 13: The list of study scenarios

	FIT (1–10 year)	FIT (11-20 year)	Electricity cost	Battery DOD
Scenario 1	Single power generation	LPS	EPS1	80%
Scenario 2	Single power generation	HPS	EPS1	80%
Scenario 3	Single power generation	LPS	EPS2	80%
Scenario 4	Single power generation	HPS	EPS2	80%
Scenario 5	Single power generation	LPS	EPS3	80%
Scenario 6	Single power generation	HPS	EPS3	80%
Scenario 7	Single power generation	LPS	EPS1	60%
Scenario 8	Single power generation	HPS	EPS1	60%
Scenario 9	Single power generation	LPS	EPS2	60%
Scenario 10	Single power generation	HPS	EPS2	60%
Scenario 11	Single power generation	LPS	EPS3	60%
Scenario 12	Single power generation	HPS	EPS3	60%
Scenario 13	Single power generation	LPS	EPS1	40%
Scenario 14	Single power generation	HPS	EPS1	40%
Scenario 15	Single power generation	LPS	EPS2	40%
Scenario 16	Single power generation	HPS	EPS2	40%
Scenario 17	Single power generation	LPS	EPS3	40%
Scenario 18	Single power generation	HPS	EPS3	40%
Scenario 19	Double power generation	LPS	EPS1	80%
Scenario 20	Double power generation	HPS	EPS1	80%
Scenario 21	Double power generation	LPS	EPS2	80%

Scenario 22	Double power generation	HPS	EPS2	80%
Scenario 23	Double power generation	LPS	EPS3	80%
Scenario 24	Double power generation	HPS	EPS3	80%
Scenario 25	Double power generation	LPS	EPS1	60%
Scenario 26	Double power generation	HPS	EPS1	60%
Scenario 27	Double power generation	LPS	EPS2	60%
Scenario 28	Double power generation	HPS	EPS2	60%
Scenario 29	Double power generation	LPS	EPS3	60%
Scenario 30	Double power generation	HPS	EPS3	60%
Scenario 31	Double power generation	LPS	EPS1	40%
Scenario 32	Double power generation	HPS	EPS1	40%
Scenario 33	Double power generation	LPS	EPS2	40%
Scenario 34	Double power generation	HPS	EPS2	40%
Scenario 35	Double power generation	LPS	EPS3	40%
Scenario 36	Double power generation	HPS	EPS3	40%

4.9 Calculation assumptions

The study develops 36 scenarios to assess the cost or benefits of installing residential integrated PV-battery storage systems in a 20-year period time. Analysis of each scenario is conducted based on the following assumptions:

Single power generation:

- Battery is only used for one cycle a day from 7am to

10:59pm everyday.

- While PV is selling excessive amount of electricity to the grid, electric discharge from the battery is shut off. Battery is only discharged when electricity from PV cannot meet the electricity demand.
- Battery is preferentially used to supplement the Day time electricity demand. If there is any electricity remaining in the battery, it is used to complement the Living time electricity demands until it meets all of the demand or until it runs out of its capacity.
- Battery does not discharge electricity during the Night time.
- Battery is charged during the Night time, the period with the cheapest price of electricity. Battery is fully charged before it is used the next day. The battery is re-charged only to refill the amount used.

Double power generation:

- Battery is only used for one cycle a day from 7am to 10:59pm everyday.
- All of the electricity generated from PV during the Day time is sold to the grid. Electricity demand for household purposes are used from electric

discharge from the battery. However, if the household consumption exceeds the available amount of electricity in a battery, the electricity from PV is used for household purposes. In such cases, the excess amount of electricity is sold to the grid.

- Electricity generated from PV during the Living time and the Night time is used for household purposes. Only the excess amount of electricity is sold to the grid.
- Battery is preferentially used to supplement the Day time electricity demand. If there is any electricity remaining in the battery, it is used to complement the Living time electricity demands until it meets all of the demand or until it runs out of its capacity.
- Battery does not discharge electricity during the Night time.
- Battery is charged during the Night time, the period with the cheapest price of electricity. Battery is fully charged before it is used the next day. The battery is re-charged only to refill the amount used.

PV generated electricity after 11th year:	• Electricity generated from PV is sold to the grid if it has a surplus after it is being preferentially used for household purposes and if the set FIT price is higher than the electricity price in the Night time (11pm to 7 am). Otherwise, the excess amount of electricity is first used to recharge the battery. If the excess amount of electricity is still available, then it is sold to the grid. ** Refer section 4.10.4 for information of when FIT exceeds the Night time electricity price.*
Discount rate:	• A discount rate of 2% is used.

4.10 Calculation performed using Microsoft Excel

A set of five steps will be undertaken in this study to calculate and estimate the economic values of integrated PV-battery systems in NPV and IRR.

Step 1. Calculate electricity cost

Step 2. Estimate amount of available solar PV generation

Step 3. Calculate revenue from the savings in electricity consumption

Step 4. Calculate revenue from FIT

Step 5. Conduct IRR and NPV analysis

4.10.1 Price of electricity

The annual price of electricity will be calculated by summing the daily electricity consumption. Based on Table 11 on page 82, the daily electricity price for weekdays *EPwd* and hourly electricity price for weekends *EPwe* will be calculated using the following equations.

$$EPwd = \{(E_{C1} \times E_{LT}) + (E_{C2} \times E_{DT}) + (E_{C3} \times E_{NT})\} \times EPS^{1-YR}\ [yen] \qquad (9)$$

where, E_{C1} is the electric consumption data from 7am to 9:59am and 5pm to 10:59pm, E_{LT} is the Living time electricity price (27.32 yen/kWh), E_{C2} is the electric consumption data from 10am to 4:59am, and E_{DT} is the Day time electricity price (35.54 or 38.80 yen/kWh depending on the date), E_{C3} is the electric consumption data from 11pm to 6:59am, E_{NT} is the Night time electricity price (13.10 yen/kWh), EPS is electricity price scenario, *EPS1, EPS2* or *EPS3*, YR is the year.

$$EPwe = \{(E_{C4} \times E_{LT}) + (E_{C5} \times E_{NT})\} \times EPS^{1-YR}\ [yen] \qquad (10)$$

where, E_{C4} is the electric consumption data from 7am to 10:59pm, E_{LT} is the Living time electricity price (27.32 yen/kWh), E_{C5} is the electric consumption data from 11pm to 6:59am, and E_{NT} is the Night time electricity price (13.10 yen/kWh), EPS is electricity price scenario, *EPS1, EPS2* or *EPS3*, YR is the year.

4.10.2 Estimation of solar PV generation

Equation 3 in section 4.7.1.2 will be used to calculate expected hourly PV generation amount of the first year Ep_1. Similarly, equation 4 in section 4.7.1.2 will be used to calculate hourly PV generation amount from the second year onward Ep_{2-20}.

4.10.3 Calculate revenue from the savings in electricity consumption

This study will define the revenue from the savings in electricity consumption CS as the difference between the original cost of electricity bills and the new cost of electricity bills. Based on the actual electricity consumption data and contracted electricity prices provided from the owners of House A and House B, original annual electricity costs are derived as follow:

House A: 188,284 yen or 18.44yen/kWh (average annual electricity cost for 2015 and 2016)

House B: 155,436 yen or 23.6 yen/kWh (cost in 2016).

For House A, since the study will use a 2 year actual electricity consumption data (data in 2015 and 2016), the savings presented for House A will be the mean of 2015 and 2016 savings.

The new cost of the electricity bills will be calculated based on the assumptions stated on page 83. Based on such information, revenues from the savings in electricity consumption will be calculated as followings:

- House A, $CS_{HOUSE\ A}$

$$CS_{HOUSE\ A} = 188{,}284 - NR\ [yen] \tag{11}$$

where, NR is the cost of electricity consumption in different scenarios.

- House B, $CS_{HOUSE\ B}$

$$CS_{HOUSE\ B} = 155{,}436 - NR\ [yen] \tag{12}$$

where, NR is the cost of electricity consumption in different scenarios.

4.10.4 Calculate revenue from FIT (1- 10, 11-20)

Estimating the revenue from FIT is one of the necessary steps to analyze the overall financial performance of integrated PV-battery systems. Since the study divides FIT into two main categories, which are FIT for the first 10 years and FIT for the last 10 years, each FIT will be calculated using the below equations.

- FIT revenue from 1^{st} to 10^{th} year

FIT from 1^{st} to 10^{th} year $PF_{1\text{-}10}$ will be calculated using the following equation:

$$PF_{1-10} = E_{PV} \times C_{FIT1-10} \, [yen] \tag{13}$$

where, E_{PV} is electricity generated from PV, $C_{FIT1-10}$ is the price set by FIT, which is 31 yen/kWh for single power generation and 25 yen/kWh for double power generation.

- FIT price from 11^{th} to 20^{th} year

This study sets two assumptions for FIT price from 11^{th} to 20^{th} year, *LPS* and *HPS*; therefore, two equations will be used to calculate revenues in each scenario.

FIT from 11^{th} to 20^{th} year under the *LPS* scenario $PFLPS_{11\text{-}20}$ will be calculated using the following equation:

$$PFLPS_{11-20} = E_{PV} \times C_{FITLPS} \, [yen] \tag{14}$$

where, E_{PV} is electricity generated from PV, C_{FITLPS} is *LPS*, 9.4 yen/kWh.

FIT from 11th to 20th year under the *HPS* scenario $PFHPS_{11\text{-}20}$ will be calculated using the following equation:

$$PFHPS_{11-20} = E_{PV} \times C_{FITHPS}\ [yen] \qquad (15)$$

where, E_{PV} is electricity generated from PV, C_{FITHPS} is *HPS*, 14.5 yen/kWh.

As mentioned in section 4.9, PV generated electricity price after 11th year will preferably be sold to the grid, if the set FIT is higher than the Night time electricity price after it is used for household purposes, otherwise PV generated electricity will preferably used to recharge the battery. Since the set LPS price is lower than the set Night time electricity price, PV electricity will be preferably used to recharge the battery in all scenarios. In case of the *HPS*, its set price is 14.5 yen, which is higher than the set Night time electricity price. In the *HPS* cases, all scenarios in *EPS1* and until 9th year in *EPS2*, and until 3rd year in *EPS3* will be preferably sold to the grid. After these years, the Night time electricity price will be higher than FIT price, thus, PV generated electricity will be first used to recharge the battery and only remaining electricity, if there is, will be sold to the grid.

4.10.5 Conduct NPV and IRR analysis

After the above calculations are performed, the study will calculate NPV and IRR of integrated PV-battery systems under 36 scenarios.

4.10.5.1NPV

NPV of the systems *NPV* will be calculated using the below equation.

$$NPV = (CAPEX + OPEX) \times -1 + \sum_{t=1}^{20} \frac{P_t}{(1+r)^t} \; [yen] \tag{16}$$

where, $CAPEX$ is the investment cost during the study period, $OPEX$ is the maintenance cost during the study period, t is cash flow time period, P is net cash flow, and r is a discount rate (set at 2%). P is composed of the sum of the CS and the revenues from FIT.

As mentioned in section 4.9, electricity generated from PV systems after 11th year will preferably be sold to the grid, if the set FIT is higher than the price of electricity in Night time after it is used for household purposes; otherwise PV generated electricity will be used to recharge the battery. Since the set *LPS* price is lower than the set Night time electricity price, PV electricity will be used, preferably, to recharge the battery in all scenarios. In case of the *HPS*, its set price is 14.5 yen, which is higher than the set Night time electricity price. In the *HPS* cases, all scenarios in *EPS1* and until 9th year in *EPS2*, and until 3rd year in *EPS3* will be sold, preferably, to the grid. After these years, the Night time electricity price will be higher than FIT price, thus, PV generated electricity will be used, first, to recharge the battery and the remainder of the electricity will be sold to the grid, if any.

4.10.5.2IRR

IRR of the systems under different scenarios will be calculated using the IRR function in *Microsoft Excel.* IRR is an investments indicator, which assesses the expected profit of an investment in a percentage unit. If NPV value is lower than 0, it is expected that a project will lose its capital, thus it does not present any value in making an investment. Since IRR is supplementary information to judge the value of an investment based on NPV values, this study will only calculate IRR using the formula in *Microsoft Excel* if NPV of a selected scenario presents positive values.

Furthermore, since this study is focused on analyzing the financial performance of integrated PV-battery systems over a 20-year time period using a variety of scenarios rather than making an investment recommendation, a hurdle rate will not be set.

4.11 Sensitivity analysis

A sensitivity analysis will be performed for scenarios that showed negative NPV. In this study, sensitivity analysis will be performed based on one specific input parameter, which is the cost of battery storage systems. One of the rationales of studying PV-battery systems is to verify the impact of the high cost of battery systems to the overall profitability of PV-battery systems. Therefore, this study will aim to identify the cost of reduction for batteries necessary in order to generate a break-even or NPV=0 in each scenario. Two conditions under each scenario will be considered in determining a break-even point: 1) battery storage systems are subsidized; and 2) the systems are not subsidized.

Chapter 5: Results, Findings and Discussions

5.1 Introduction

This chapter presents and discusses the results of numerical analyses. This section provides information on which scenarios achieved positive economical values for integrated PV-battery systems as measured by NPV. IRR is also presented for scenarios with positive NPV values. The results of sensitivity analysis are also presented and explained to demonstrate the impact of the cost of battery storage systems. These are used to formulate responses to the research questions of this study.

5.2 Results

Figure 16 and 17 compare annual electricity consumption between original, single power generation, and double power generation for House A and House B, respectively. Figure 18 and 19 present the comparison of monthly electricity consumption between original, single power generation, and double power generation by time of use period for House A and House B, respectively.

Table 14 and Table 15 present the results of calculations. Table 14 presents the results for House A and Table 15 is the results for House B. Table 16, 17, 18, and 19 present the results of sensitive analysis. As mentioned in section 4.11, sensitivity analysis is conducted on the cost of battery storage systems.

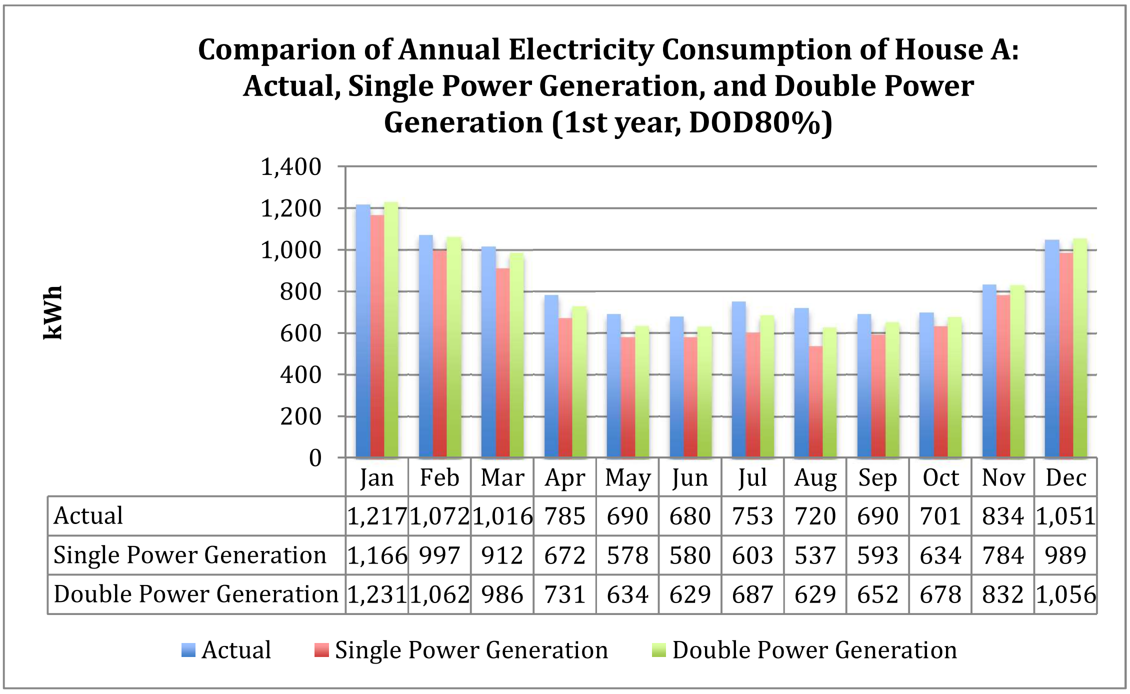
5.3 Findings

Figure 16 and 17 compare annual electricity consumption between original electricity consumption, the electricity consumption at single power generation, the electricity consumption at double power generation for House A and B. Due to space constraints, comparison of the first year electricity consumption data when DOD 80% are presented. Based on Figure 16, for House A, the single power generation scenario reduces electricity consumption by an average of 12.3% or 97kWh. The highest electricity consumption decrease occurs in August, which is a 25.5% reduction from the original electricity consumption. For the double power generation scenario, electricity consumption decreases by an average of 4.6%; electricity consumption but increases from the original electricity consumption level in January and December.

For House B, the single power generation scenario reduces electricity consumption by an average of 28.7% or 153 kWh (Figure 17). During the year, the highest reduction in consumption is in May, at 38.7%. In the case of double power generation scenario, electricity consumption decreases by an average of 7.5%. The results of both single power generation and double power generation scenarios indicate that House B receives more benefit in terms of electricity consumption reduction than House A.

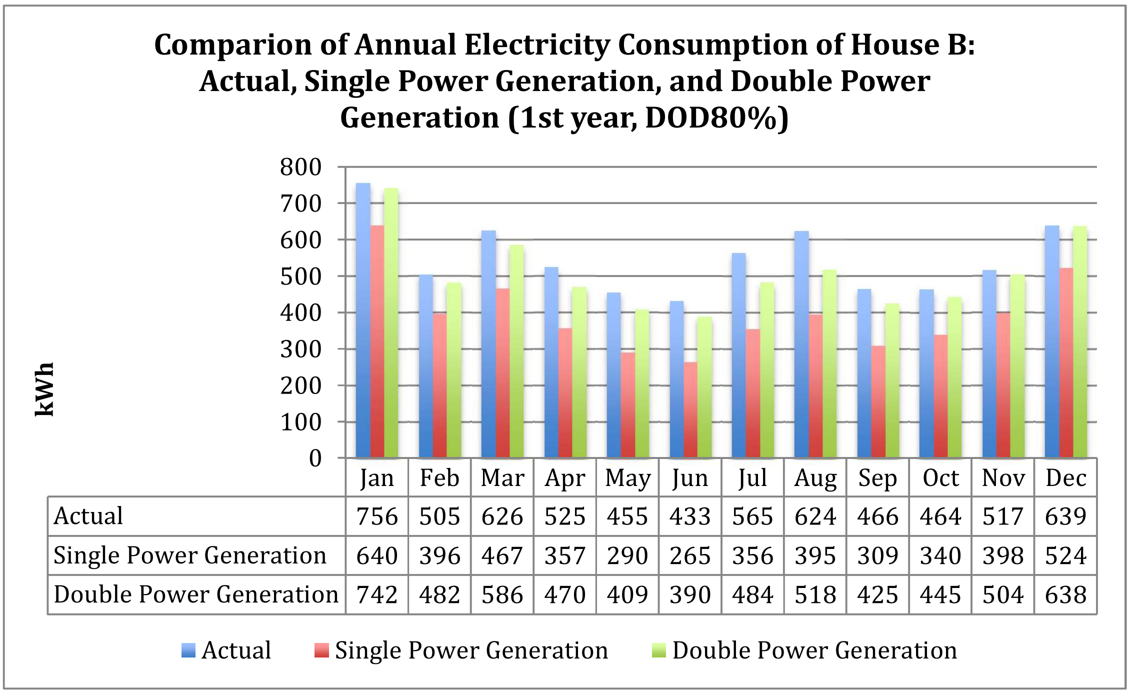
Figure 18 and Figure 19 present comparisons of monthly electricity consumption between original electricity consumption, the electricity consumption at single power generation, the electricity consumption at double power generation for House A and B. Similar to Figure 16 and 17, the graphs present the first year of electricity consumption data when DOD was set at 80%. These figures compare and demonstrate the change in electricity consumption pattern from the original consumption pattern. As can be seen, by installing PV-battery systems, both houses successfully reduce electricity consumption during the time with the highest electricity cost, the Day time. Except for December for House A and January for House B, no electricity was consumed from the grid during the Day time.

The figures also explain the cause of higher electricity consumption for double power generation compared to single power generation. As it can be seen, for double power generation, there is higher electricity consumption during the Living time compared to single power generation scenario. This is attributed mainly to the difference of using battery when PV generates electricity. As explained in section 4.9, for single power generation, household electricity is distributed from PV systems when it generates electricity. Electricity charged in a battery is only used if the electricity generated from PV panels cannot meet household electricity demand. On the other hand, the benefit of double power generation is the ability to sell as much electricity as possible to the grid from PV generation to earn higher profit from FIT. Thus, a battery is used to provide electricity for household applications even when PV panels generate electricity. As a result, the number of times the battery is fully used is higher than that of single power generation scenarios. In addition, double power generation consumes more Living time electricity than that of single power generation. This is because, preferable, electricity charged in battery is used during the Day time. If all of the electricity is used during the Day time, then the battery does not have the capacity to supplement the electricity demand during the Living time, which will then require the house to purchase electricity from the grid.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Actual	1,217	1,072	1,016	785	690	680	753	720	690	701	834	1,051
Single Power Generation	1,166	997	912	672	578	580	603	537	593	634	784	989
Double Power Generation	1,231	1,062	986	731	634	629	687	629	652	678	832	1,056

Figure 16: Comparison of annual electricity consumption of House A: actual, single power generation, and double power generation (1st year, DOD80%)
* Actual: Actual electricity consumption



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Actual	756	505	626	525	455	433	565	624	466	464	517	639
Single Power Generation	640	396	467	357	290	265	356	395	309	340	398	524
Double Power Generation	742	482	586	470	409	390	484	518	425	445	504	638

Figure 17: Comparison of annual electricity consumption of House B: actual, single power generation, and double power generation (1st year, DOD80%)

* Actual: Actual electricity consumption

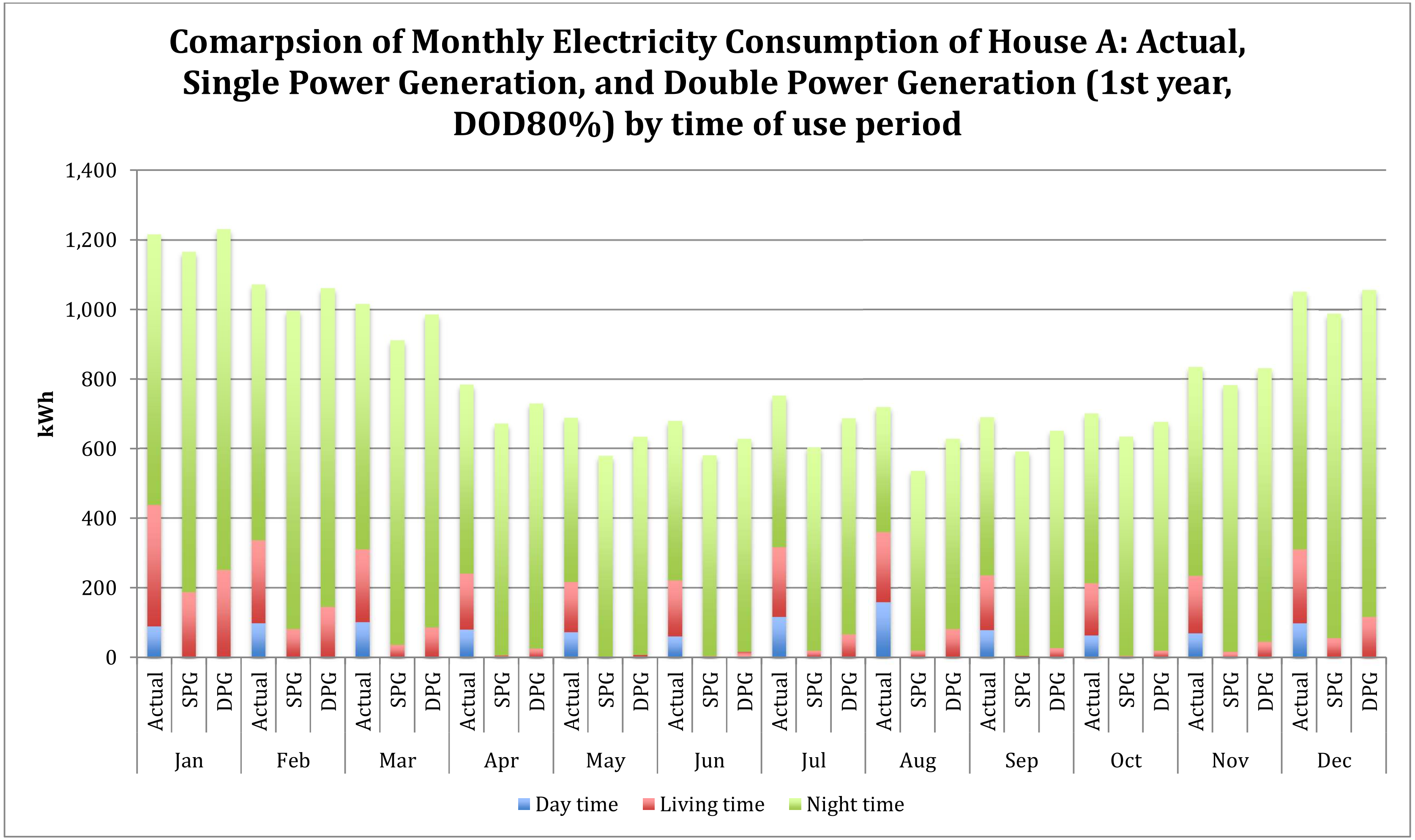


Figure 18: Comparison of monthly electricity consumption of House A: actual, single power generation, and double power generation (1st year, DOD80%) by time of use period

* Actual: Actual electricity consumption, SPG: Electricity consumption under single power generation, DPG: Electricity consumption under double power generation

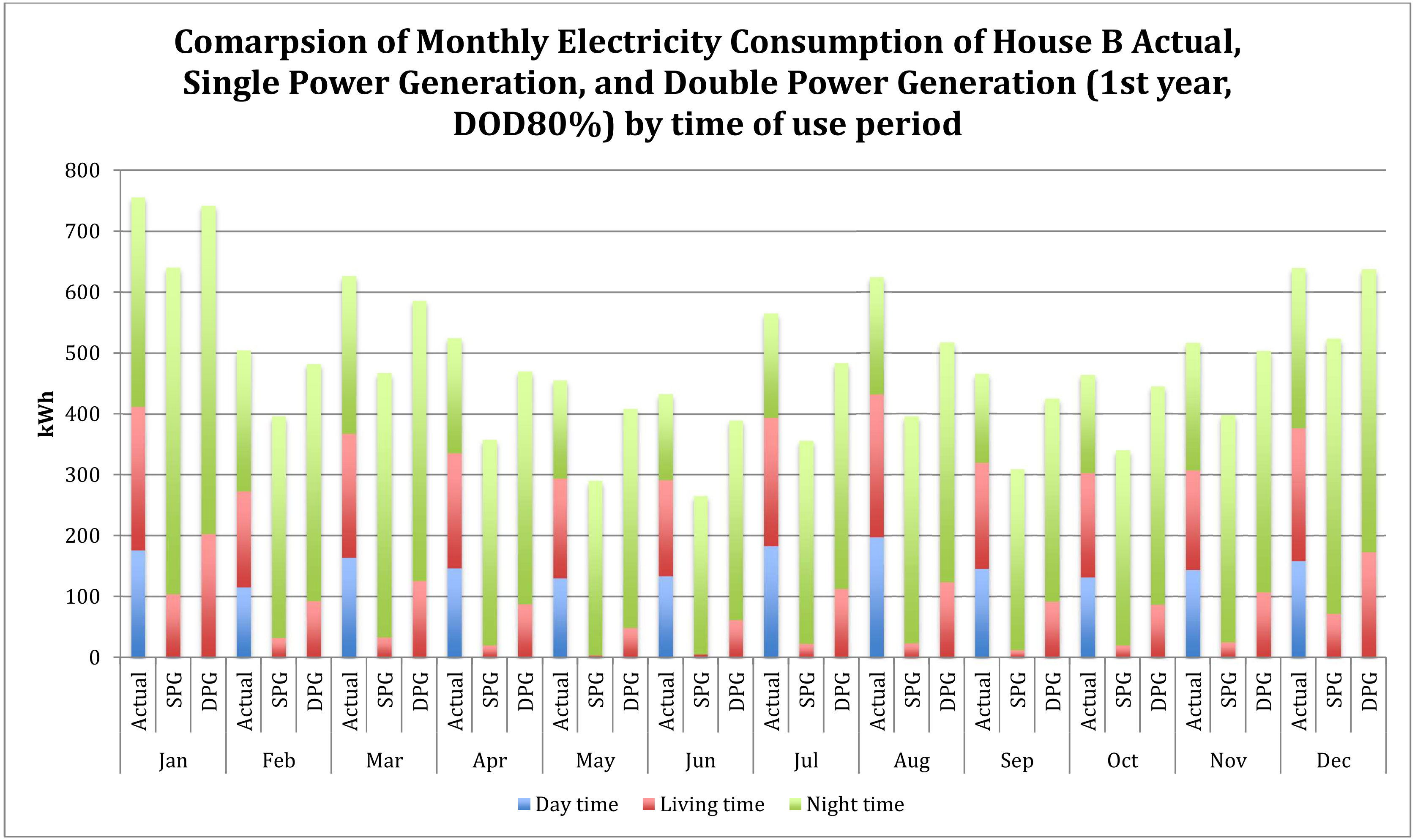


Figure 19: Comparison of monthly electricity consumption of House B: actual, single power generation, and double power generation (1st year, DOD80%) by time of use period

* Actual: Actual electricity consumption, SPG: Electricity consumption under single power generation, DPG: Electricity consumption under double power generation

5.4 Discussions

5.4.1 Research Question 1

Under what conditions will PV + battery storage systems create positive economic returns?

Table 14 and 15 present the financial analysis of integrated PV-battery systems for House A and House B. Based on Table 14, all of the scenarios did not demonstrate positive economic returns for House A. For House B, three scenarios from the single power generation category, scenarios 11, 12 and 17 and one scenario from the double power generation category, scenario 29 presented positive economic returns. Among these scenarios, scenario 11 recorded the highest NPV and IRR, which were NPV of 194,487 yen and IRR of 2.89%.

From the results, the following points can be concluded:

- For House A, there is no economic benefit to investment in the integrated PV-battery system.
- For House B, PV-battery systems create positive economic return for scenarios 11, 12, 17 and 29. Otherwise, there is no economic benefit to investment in the integrated PV-battery system.

The reason why House B demonstrated better results can be attributed to the higher electricity consumption during the day when PV panels generate electricity.

Figure 20 presents the relationship between PV generation and electricity consumption timings for House A and House B. As mentioned in Chapter 4, the study incorporated 0.5% annual PV degradation factor; however, due to a space constraint, this study only presents the graph of the 11th year. As it can be seen, the amount of PV generation exceeds the amount of electricity demand for House A when PV generates electricity. Compared to House A, household electricity demand when PV panels generate electricity for House B is high when the PV panels generate electricity, thus electricity from PV is used to meet the energy demand for household use. As a result, less excess electricity generated from PV systems can be used either to charge the battery or to sell it to the grid compared to House A.

If a large volume of electricity is consumed when PV generates electricity, consumers can 1) use electricity from PV systems for household purposes, which can contribute to lower electricity bills; and 2) sell the excess amount of electricity to the grid or charge the battery. However, if the household electricity consumption during when PV generates electricity is less, only a small amount of electricity is used for household purposes. In such cases, PV generated electricity can be used to recharge the battery; but the remaining electricity is sold to the grid. As the study assumed that FIT price would drop from 11th year, the revenue from FIT also decreases; thus, consumers receive more benefits if they use it for household purposes and for recharging the battery. Furthermore, if the FIT price is lower than the cost to purchase electricity, it would create more economic profit if PV generated electricity is used for household purposes than for sale to the grid. Thus, calculation results for House B recorded better results than those of House A.

Regardless of scenarios recording positive or negative NPV values, it was confirmed that results improved when there was an increase in the price of electricity. It was found that the higher the rate of increase in electricity price, the better the financial results were. The results demonstrated that *EPS3* demonstrated the best financial performance results followed by scenarios under *EPS2*. The worst economic returns were recorded when there is no change in the electricity price, *EPS1*.

It has been confirmed that the four scenarios that presented positive results in Table 15 were recorded when electricity price was set at *EPS3*. These findings suggest that the benefit of installing integrated PV-battery systems increase under a condition in which electricity price increases every year at a rate of 3.62%/year.

Amongst different assumed DOD scenarios, it was found that utilizing a battery at DOD 60% demonstrated the best performance result followed by the result of DOD 40% scenarios. Among the four scenarios that indicated positive NPV values from House B, the highest return was recorded, when DOD was calculated at 60%, which is scenario 11. Scenarios at DOD80% presented the poorest financial results due to shorter battery life. This is due to the replacement of a battery in the 17th year having a major impact on the total financial performance.

In summary, while integrated PV-battery systems could decrease electricity consumption or shift electricity consumption patterns from using expensive electricity to using cheaper electricity for both houses, economic analysis indicated that the systems would not generate positive economic returns under any scenario for House A. Thus, it is not recommended that House A install the systems. In the case of House B, 4 out of 36 scenarios showed positive NPV values with IRR of between 2 to 3%. If conditions are set to those four scenarios, the investment in installation of the PV-battery systems can be justified.

Table 14: NPV and IRR results of House A under 36 scenarios

	NPV (¥)	IRR (%)		NPV (¥)	IRR (%)
Scenario 1	-885,191		Scenario 19	-1,139,764	
Scenario 2	-768,900		Scenario 20	-982,117	
Scenario 3	-765,518		Scenario 21	-985,539	
Scenario 4	-771,488		Scenario 22	-996,293	
Scenario 5	-411,058		Scenario 23	-658,300	
Scenario 6	-440,336		Scenario 24	-687,578	
Scenario 7	-570,399		Scenario 25	-806,905	
Scenario 8	-460,068		Scenario 26	-696,573	
Scenario 9	-422,541		Scenario 27	-670,922	
Scenario 10	-468,366		Scenario 28	-716,748	
Scenario 11	-97,356		Scenario 29	-368,719	
Scenario 12	-184,004		Scenario 30	-455,367	
Scenario 13	-657,718		Scenario 31	-909,547	
Scenario 14	-560,012		Scenario 32	-811,841	
Scenario 15	-525,421		Scenario 33	-415,484	
Scenario 16	-554,594		Scenario 34	-817,082	
Scenario 17	-234,868		Scenario 35	-517,957	
Scenario 18	-302,421		Scenario 36	-585,509	

Table 15: NPV and IRR results of House B under 36 scenarios

	NPV (¥)	IRR (%)		NPV (¥)	IRR (%)
Scenario 1	-762,272		Scenario 19	-900,591	
Scenario 2	-633,019		Scenario 20	-771,338	
Scenario 3	-553,386		Scenario 21	-708,152	
Scenario 4	-564,276		Scenario 22	-719,041	
Scenario 5	-94,312		Scenario 23	-280,990	
Scenario 6	-123,339		Scenario 24	-310,017	
Scenario 7	-422,852		Scenario 25	-563,582	
Scenario 8	-342,347		Scenario 26	-483,077	
Scenario 9	-229,588		Scenario 27	-382,853	
Scenario 10	-286,377		Scenario 28	-439,641	
Scenario 11	194,487	2.89	Scenario 29	16,755	2.08
Scenario 12	100,144	2.48	Scenario 30	-77,587	
Scenario 13	-506,702		Scenario 31	-644,030	
Scenario 14	-432,218		Scenario 32	-569,547	
Scenario 15	-328,001		Scenario 33	-472,542	
Scenario 16	-363,631		Scenario 34	-508,172	
Scenario 17	64,100	2.30	Scenario 35	-94,396	
Scenario 18	-4,482		Scenario 36	-162,979	

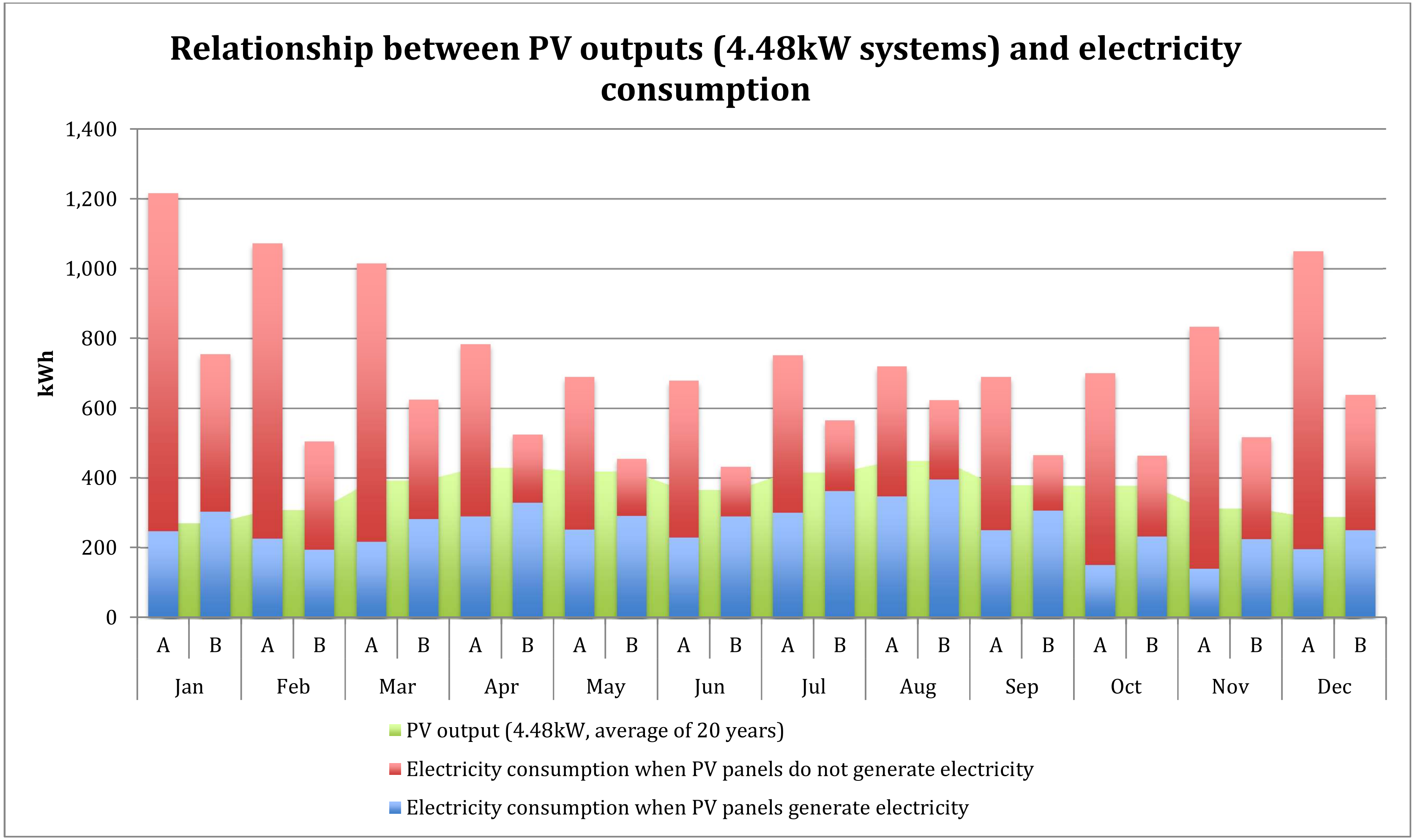


Figure 20: Relationship between PV outputs and electricity consumption timings
* A: House A, B: House B

5.4.2 Research Question 2

Are economic incentives necessary for PV + battery storage systems to be profitable?

Table 16 and 17 present the results of sensitivity analysis for scenarios with and without subsidies. The tables present a break-even cost of the battery, and yen/kWh. They also present the required cost of original battery, 1,417,000 yen, to break-even. From the tables, the following findings can be observed:

- For House A, the lowest and highest break-even cost of battery is 48,713 yen/kWh and 184,630 yen/kWh, respectively.
- For House B, the lowest and highest break-even cost of battery is 79,789 yen/kWh and 184,551 yen/kWh, respectively.
- In both cases, break-even cost greatly depends on the rate of change in annual electricity price. The higher the rate of increase in electricity price, the less need for reducing the original cost of the battery.
- DOD also affects the break-even point of the battery. DOD 60% requires the lowest cost reduction of battery followed by DOD 40%. Scenarios at DOD80% require the most cost deduction in battery for PV-battery systems to hit break-even point, because the replacement of a battery burdens the total economic performance of PV-battery systems.

As mentioned in section 3.15, ANRI has announced a target, to reduce the cost of residential batteries to 90,000 yen/kWh by 2020, to provide an attractive solution to consumers through policy driven actions (2016). If this cost is achieved, 30 scenarios out of 36 scenarios for both House A and House B would create NPV=0 with subsidy. However, 6 scenarios for House A would not reach a break-even point even if the cost is reduced to 90,000 yen/kWh.

Table 18 and 19 present the results of sensitivity analysis for scenarios without subsidies. From the tables, following findings can be observed:

- For House A, the lowest and highest break-even cost of battery is 8,014 yen/kWh and 109,591 yen/kWh, respectively.
- For House B, the lowest and highest break-even cost of battery is 38,348 yen/kWh and 99,719 yen/kWh, respectively.
- Similar to Table 16 and 17, break-even cost greatly depends on the rate of change in annual electricity price and DOD.

Without subsidies, the break-even cost of battery is lower than what ANRI proposes, 90,000 yen/kWh, for most cases. Thus, from sensitivity analysis, it can be concluded that economic incentives greatly contribute to making PV + battery storage systems profitable, at least for a short period until the cost of battery reaches 90,000 yen/kWh or lower. As the current battery tested for this study is still at a high cost, at 354,000 yen/kWh, it requires a substantial decrease in the cost of battery to reach the break-even point. For PV-battery systems to show positive economic performance without subsidies, the cost needs to be further decreased from what ANRI proposes to achieve by 2020, which is 90,000 yen/kWh. Therefore, while a continuous subsidy programs are needed, a policy to enhance the decrease in the cost of a battery is also required for the system to be economically feasible based solely on private residential benefits.

Table 16: Breakeven costs for batteries by scenario: House A with subsidy

Scenario	**The cost of battery (¥)**	**¥/kWh of capacity**	**Cost deduction (¥)**	**Cost deduction (%)**	Scenario	**The cost of battery (¥)**	**¥/kWh of capacity**	**Cost deduction (¥)**	**Cost deduction (%)**
1	550,198	76,416	-866,802	61.2	19	350,730	48,713	-1,066,270	75.2
2	697,680	96,900	-719,320	50.8	20	498,212	69,196	-918,788	64.8
3	700,844	97,339	-716,156	50.5	21	495,010	68,751	-921,990	65.1
4	695,259	97,339	-721,741	50.9	22	484,950	67,354	-932,050	65.8
5	1,032,447	143,395	-384,553	27.1	23	801,148	111,271	-615,852	43.5
6	1,005,057	139,591	-411,943	29.1	24	773,758	107,466	-643,242	45.4
7	903,373	125,468	-513,627	36.2	25	690,407	95,890	-726,593	51.3
8	1,002,723	139,267	-414,277	29.2	26	789,757	109,688	-627,243	44.3
9	1,036,515	143,960	-380,485	26.9	27	812,855	112,897	-604,145	42.6
10	995,250	138,229	-421,750	29.8	28	771,591	107,165	-645,409	45.5
11	1,329,334	184,630	-87,666	6.2	29	1,084,980	150,692	-332,020	23.4
12	1,251,309	173,793	-165,691	11.7	30	1,006,955	139,855	-410,045	28.9
13	824,745	114,548	-592,255	41.8	31	597,981	83,053	-819,019	57.8
14	912,726	126,768	-504,274	35.6	32	685,962	95,273	-731,038	51.6
15	943,874	131,094	-473,126	33.4	33	1,042,870	144,843	-374,130	26.4
16	917,605	127,445	-499,395	35.2	34	681,243	94,617	-735,757	51.9
17	1,205,508	167,432	-211,492	14.9	35	950,596	132,027	-466,404	32.9
18	1,144,679	158,983	-272,321	19.2	36	889,767	123,579	-527,233	37.2

Table 17: Breakeven costs for batteries by scenario: House B with subsidy

Scenario	**The cost of battery (¥)**	**¥/kWh of capacity**	**Cost deduction (¥)**	**Cost deduction (%)**	Scenario	**The cost of battery (¥)**	**¥/kWh of capacity**	**Cost deduction (¥)**	**Cost deduction (%)**
1	703,880	97,761	-713,120	50.3	19	574,481	79,789	-842,519	59.5
2	824,799	114,555	-592,201	41.8	20	695,399	96,583	-721,601	50.9
3	899,297	124,902	-517,703	36.5	21	754,511	104,793	-662,489	46.8
4	889,110	123,488	-527,890	37.3	22	744,324	103,378	-672,676	47.5
5	1,328,769	184,551	-88,231	6.2	23	1,154,128	160,296	-262,872	18.6
6	1,301,614	180,780	-115,386	8.1	24	1,126,974	156,524	-290,026	20.5
7	1,036,235	143,922	-380,765	26.9	25	909,512	126,321	-507,488	35.8
8	1,108,727	153,990	-308,273	21.8	26	982,004	136,389	-434,996	30.7
9	1,210,263	168,092	-206,737	14.6	27	1,072,253	148,924	-344,747	24.3
10	1,159,126	160,990	-257,874	18.2	28	1,021,116	141,822	-395,884	27.9
11					29				
12					30	1,347,134	187,102	-69,866	4.9
13	960,731	133,435	-456,269	32.2	31	837,070	116,260	-579,930	40.9
14	1,027,801	142,750	-389,199	27.5	32	904,140	125,575	-512,860	36.2
15	1,121,645	155,784	-295,355	20.8	33	991,491	137,707	-425,509	30.0
16	1,089,561	151,328	-327,439	23.1	34	959,407	133,251	-457,593	32.3
17					35	1,331,999	185,000	-85,001	6.0
18	1,412,963	196,245	-4,037	0.3	36	1,270,242	176,423	-146,758	10.4

Table 18: Breakeven costs for batteries by scenario: House A without subsidy

Scenario	The cost of battery (¥)	¥/kWh of capacity	Cost deduction (¥)	Cost deduction (%)	Scenario	The cost of battery (¥)	¥/kWh of capacity	Cost deduction (¥)	Cost deduction (%)
1	261,884	36,373	-1,155,116	81.5	19	145,034	20,144	-1,271,966	89.8
2	348,281	48,372	-1,068,719	75.4	20	231,430	32,143	-1,185,570	83.7
3	350,134	48,630	-1,066,866	75.3	21	229,555	31,883	-1,187,445	83.8
4	346,863	48,175	-1,070,137	75.5	22	223,661	31,064	-1,193,339	84.2
5	544,391	75,610	-872,609	61.6	23	408,894	56,791	-1,008,106	71.1
6	528,346	73,381	-888,654	62.7	24	392,848	54,562	-1,024,152	72.3
7	363,091	50,429	-1,053,909	74.4	25	150,125	20,851	-1,266,875	89.4
8	462,442	64,228	-954,558	67.4	26	249,476	34,649	-1,167,524	82.4
9	496,233	68,921	-920,767	65.0	27	272,574	37,858	-1,144,426	80.8
10	454,969	63,190	-962,031	67.9	28	231,309	32,126	-1,185,691	83.7
11	789,053	109,591	-627,947	44.3	29	544,698	75,653	-872,302	61.6
12	711,028	98,754	-705,972	49.8	30	466,674	64,816	-950,326	67.1
13	284,463	39,509	-1,132,537	79.9	31	57,700	8,014	-1,359,300	95.9
14	372,445	51,728	-1,044,555	73.7	32	145,681	20,233	-1,271,319	89.7
15	403,593	56,055	-1,013,407	71.5	33	502,588	69,804	-914,412	64.5
16	377,324	52,406	-1,039,676	73.4	34	140,962	19,578	-1,276,038	90.1
17	665,227	92,393	-751,773	53.1	35	410,315	56,988	-1,006,685	71.0
18	604,398	83,944	-812,602	57.3	36	349,486	48,540	-1,067,514	75.3

Table 19: Breakeven costs for batteries by scenario: House B without subsidy

Scenario	**The cost of battery (¥)**	**¥/kWh of capacity**	**Cost deduction (¥)**	**Cost deduction (%)**	Scenario	**The cost of battery (¥)**	**¥/kWh of capacity**	**Cost deduction (¥)**	**Cost deduction (%)**
1	351,913	48,877	-1,065,087	75.2	19	276,109	38,348	-1,140,891	80.5
2	422,749	58,715	-994,251	70.2	20	346,945	48,187	-1,070,055	75.5
3	466,390	64,776	-950,610	67.1	21	381,573	52,996	-1,035,427	73.1
4	460,422	63,948	-956,578	67.5	22	375,605	52,167	-1,041,395	73.5
5	717,980	99,719	-699,020	49.3	23	615,673	85,510	-801,327	56.6
6	702,072	97,510	-714,928	50.5	24	599,766	599766	-817,234	57.7
7	495,954	68,883	-921,046	65.0	25	369,230	51,282	-1,047,770	73.9
8	568,446	78,951	-848,554	59.9	26	441,722	61,350	-975,278	68.8
9	669,981	93,053	-747,019	52.7	27	531,971	73,885	-885,029	62.5
10	618,845	85,951	-798,155	56.3	28	480,835	66,783	-936,165	66.1
11					29				
12					30	806,853	112,063	-610,147	43.1
13	420,449	58,396	-996,551	70.3	31	296,789	41,221	-1,120,211	79.1
14	487,519	67,711	-929,481	65.6	32	363,859	50,536	-1,053,141	74.3
15	581,364	80,745	-835,636	59.0	33	451,209	62,668	-965,791	68.2
16	549,280	76,289	-867,720	61.2	34	419,126	58,212	-997,874	70.4
17					35	791,717	109,961	-625,283	44.1
18	872,682	121,206	-544,318	38.4	36	729,961	101,383	-687,039	48.5

Chapter 6: Conclusion

6.1 Research Summary

This research entailed studying the economic profitability of residential integrated PV-battery systems in Japan. The study analyzed the value proposition of installing the systems at two single detached residents in Kyoto, Japan. The study simulated the profitability of the systems in the form of NPV and IRR from 2017 to 2037. The study sets a variety of conditions as input parameters and tested 36 scenarios to determine which scenarios presented positive economic returns. Furthermore, sensitivity analysis was conducted on the cost of battery to analyze its effect on the overall profitability of the systems.

The results suggested that under the assumed conditions, most of the scenarios do not create positive economic returns. They have revealed that the present cost of the battery is too high to generate a positive outcome. The results also revealed that the systems generated higher economic returns if the electricity price increased annually at a higher rate. In addition, utilizing DOD of a battery at different rates further affects the overall economic performance of the systems with a DOD 60% achieving the best returns. For scenarios which did not show positive results, sensitivity analysis was performed on the cost to determine a break-even point of PV-battery systems with and without subsidies. The results of analysis highlighted that for PV-battery systems to achieve NPV=0, a substantial decrease in the cost of battery is necessary.

6.2 Contributions to the Field

Academic Contribution

This study provides new insights for academic renewable energy research as it focuses on the residential sector, not commercial, PV-lithium-ion battery systems. As demonstrated through literature review, the use of PV-battery systems presents both challenges and opportunities in addressing the issue of climate change. While many studies have been conducted on the residential PV-battery storage systems, a study on the use of lithium-ion batteries, specifically, as a preferred battery storage system is rare as it is still an emerging topic. Moreover, the study location of Japan provides additional value, as the residential PV-lithium-ion battery storage systems remain an unexplored area. Therefore, focusing particularly on lithium-ion battery in the context of Japan provides additional knowledge and information currently not available or explored in literature.

This study further contributes academically as it distributes the research in English. While a reasonable amount of study, in English, on residential integrated PV-battery systems can be found in Europe and North America, there are only a few English articles available that focus on residential integrated PV-battery systems in Japan. Many Japanese scholarly works are written in Japanese, which places a limitation on the ability to share findings with the wider network of international scholars. Hence, by conducting a study on Japan, specifically, in English, not only offers accessibility to the information, but also offers a great opportunity to share information and showcase Japan’s advanced progress in this field to worldwide scholars.

Practical Contribution

The findings of this study hold important implications that can be shared with policy makers, the electricity industry, and consumers. Unlike many previous studies in which the average electricity consumption data from government sources or daily electricity consumption data were used, this study used real electricity consumption data that were recorded every 30 minutes for more than a year, which allowed the study to provide accurate, practical, and precise financial performance evaluation on integrated PV-battery systems. For policy makers, this study provides two important implications. First, it provides the platform to consider the type of additional policy supports required to make residential integrated PV-battery systems an economically viable option. Second, the study demonstrates that without substantial decreases in the battery cost, residential PV-battery systems do not create financial values to consumers. By comparing this study with similar studies that focus on the larger commercial scale, it can trigger a debate among policymakers for the possibility of shifting policy and its support to commercial scale battery industry rather than to residential scale battery industry. Moreover, as the use of electric vehicles has started to become common, the use of the battery installed in an electric vehicle at homes such as vehicle-to-home (V2H) may be a better financial solution for consumers as they can use the battery installed in a vehicle for household purposes as well. Together with other studies, this study provides policymakers the information necessary to develop a more comprehensive policy to implement, based on various options, as a potential means to mitigate climate change.

Increased attention to residential lithium-ion battery systems provides a great opportunity to expand for businesses in the market. For example, it is believed that with an increase in the use of residential PV-battery systems, virtual power plant (VPP) will emerge as a new energy system in Japan in the near future. To create a VPP, the participation of a large number of homeowners equipped with PV-battery systems is essential. For consumers to install battery at their homes, it is preferable to use batteries that are at a low price with a longer life cycle. For businesses in the electricity industry, this study provides an opportunity to understand a benchmark cost that enables integrated PV-battery systems to create surplus, to acquire information on the contribution of different DOD levels to the overall performance of the systems for performance enhancement through improvement of the technology of batteries to create a longer life cycle period at a higher DOD level.

For consumers, the study can be used as one of the decision making tools to determine whether to install the systems in their residents or not. This study contains comprehensive information on the conditions in which the integrated PV-battery systems create financial benefits. The result of this study demonstrates that while PV-battery systems may be a solution for consumers to install to secure energy security, they are not an economically feasible option, as they do not create financial benefits without further decrease in the cost of battery or subsidy except a few scenarios.

6.3 Limitation of the Research Design

One of the limitations is the type of battery used. There are many different types of storage batteries that are available today based on locations and needs; yet, this thesis only focuses on the use of a new lithium ion battery in the residential sector. There are several ways to justify the use of battery storage system in households; however, this study only evaluates the benefits of the use of residential battery storage system from an economic standpoint by using investment performance measures, NPV and IRR. No other indicators are considered in the analysis.

The cost of future electricity, the cost of future FIT, expected generated PV amount, the performance of a battery are all based on assumptions. Furthermore, the study does not incorporate any factors that are not identified as specified input parameters in Figure 8 in section 4.6. For example, the benefits of batteries providing a backup system during power outages were not considered.

The sample size of the study is also another limitation. The real-time actual electricity consumption data for two single-detached houses in Japan were used; hence the study draws its results from only two houses and a broader range of houses should be tested to compare results for a broader range of households.

6.4 Future Research

Integrated PV-battery systems are receiving increased attention as the demand for using the systems is increasing. This study provides a number of opportunities for future scholars to conduct research in the field. For example, expanding the study scope, such as the number of selected houses and the number of years of electricity consumption data available, can result in more comprehensive results. Since it was only in recent years that the smart meters were being installed at households in Japan, this study only selected two houses to be included in-scope of the research. As time progresses, more houses will be equipped with smart meters and a large volume of data will be available. In addition, future scholars can leverage this study to perform more analyses of the economic returns by using additional applied data, such as the actual data on PV generation and battery performance.

The economic model presented in this research can be applied to many different countries or regions; therefore, conducting a similar study in other regions will contribute academically and fill the gaps that arise from past literature. Moreover, using additional economic evaluation indicators may also contribute to this evolving field.

References

Agency for Natural Resources and Energy (ANRI). (2014) "Dai ni setsu: Bumonbetsu enerugii shouhi no doukou" [Chapter 2: Trends of energy consumotion by sectors]. *Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry (METI).* Retrieved from http://www.enecho.meti.go.jp/about/whitepaper/2016html/2-1-2.html (in Japanese)

Agency for Natural Resources and Energy (ANRI). (2012). "*Shiryou san tokuni giron ga hitsouna ronten*" [*Document 3: Points to be discussed in detail*]. [PDF document]. Japan: Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry (METI). Retrieved from http://www.meti.go.jp/committee/chotatsu_kakaku/pdf/006_03_00.pdf (in Japanese)

Agency for Natural Resources and Energy (ANRI). (2014). FY2013 Annual Report on Energy (Energy White Paper 2014) Outline. *Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry (METI).* Retrieved from http://www.meti.go.jp/english/report/downloadfiles/2014_outline.pdf

Agency for Natural Resources and Energy (ANRI). (2017). *"Saiei kanou enerugi. Kotei kakaku kaitori seido gaido book" [Guidebook on FIT]. Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry (METI).* Retrieved from http://www.enecho.meti.go.jp/category/saving_and_new/saiene/data/kaitori/2017_fit.pdf (in Japanese)

Agency for Natural Resources and Energy (ANRI). (2016). "Nihon no enerugi [Japan's Energy]. *Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry (METI).* Retrieved from http://www.enecho.meti.go.jp/about/pamphlet/pdf/energy_in_japan2015.pdf (in Japanese)

Agency for Natural Resources and Energy (ANRI). (2015) Overview of Electricity System Reform. *Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry (METI).* Retrieved from http://www.meti.go.jp/english/policy/energy_environment/electricity_system_reform/outline.html.

Agency for Natural Resources and Energy (ANRI). (2016). *"Teichiyou chikudenchi no mokuhyou kakaku settutei" [Target price of the stand-alone type battery storage systems]*. [PDF document]. Japan: Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry (METI). Retrieved from http://www.meti.go.jp/committee/kenkyukai/energy_environment/energy_resource/pdf/004_09_02.pdf (in Japanese)

Agency for Natural Resources and Energy (ANRI). (n.d.). "Kotei kakaku kaitoriseido jyouhou kouhyou you website" [Information on FIT]. *Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry (METI).* Retrieved from http://www.enecho.meti.go.jp/category/saving_and_new/saiene/statistics/index.html

Aho, T., & Virtanen, I. (1983). On relationships between ROI and IRR under inflation: A constant real cash-flow case. *European Journal of Operational Research*, *13*(3), 256-267.

Arai, T., Yabumoto, T., Hodotsuka, Y., Inaniwa, K., Kumagai, S., & Itou, T. (2004). Construction and Operation of 10kW Electric Power Storage System, *FB Techinical News, No. 60*, 29–34. Retrieved from http://158.202.43.68/research/tech/pdf/fbtn60/fbtn60_207.pdf

Asian Development Bank. (2013). Cost-benefit analysis for development: A practical guide. *Asian Development Bank.* ISBN: 978-92-9092-957-4 (Print), 978-92-9092-958-1 (PDF)

Asian Development Bank. (2017). Guidelines for the economic analysis of projects. *Asian Development Bank.* ISBN: 978-92-9257-763-6 (Print), 978-92-9257-764-3 (e-ISBN)

Askari, I. B., & Ameri, M. (2009). Optimal sizing of photovoltaic–battery power systems in a remote region in Kerman, Iran. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, *223*(5), 563–570. http://doi.org/10.1243/09576509JPE717

Blas, de. B. (2006). *Lesson 1. Net Present Value* [Pdf slides]. Retrieved from https://www.uam.es/personal_pdi/economicas/bdeblas/teaching/ucd/ecn134/lectures/slides1.pdf

Bora, D. B. (2015). Comparison between net present value and internal rate of return, *5*(12), 61–71.

Braun, M., Büdenbender, K., Magnor, D., & Jossen, A. (2009). PVself-consumption in Germany: using lithium-ion storage to increase self-consumed PVenergy. In *24th European PVSolar Energy Conference (PVSEC), Hamburg, Germany*. Retrieved from https://www.researchgate.net/profile/Martin_Braun5/publication/43248782_Photovoltaic_self-consumption_in_Germany_-_Using_lithium-ion_storage_to_increase_self-consumed_photovoltaic_energy/links/53e44b590cf21cc29fc8f428/Photovoltaic-self-consumption-in-Germ

Bruch, M., & Müller, M. (2014). Calculation of the cost-effectiveness of a PV battery system. *Energy Procedia*, *46*, 262–270. http://doi.org/10.1016/j.egypro.2014.01.181

Bull, N.R., & Tilley, R.A. (2001). Development of New Types of Zebra Batteries for VariousVehicle Applications. Paper presented at EVS 18, Berlin, October, 2001. *Beta Research and Development Ltd.*

Chen, H., Cong, T. N., Yang, W., Tan, C., Li, Y., & Ding, Y. (2009). Progress in electrical energy storage system: A critical review. *Progress in Natural Science*, *19*(3), 291–312. http://doi.org/10.1016/j.pnsc.2008.07.014

Colmenar-Santos, A., Campinez-Romero, S., Perez-Molina, C., & Castro-Gil, M. (2012). Profitability analysis of grid-connected PVfacilities for household electricity self-sufficiency. *Energy Policy*, *51*, 749–764. http://doi.org/10.1016/j.enpol.2012.09.023

Cucchiella, F., D'Adamo, I., & Gastaldi, M. (2016). PVenergy systems with battery storage for residential areas: An economic analysis. *Journal of Cleaner Production*, *131*, 460–474. http://doi.org/10.1016/j.jclepro.2016.04.157

Cuthbert, J. R., & Magni, C. A. (2016). Measuring the inadequacy of IRR in PFI schemes using profitability index and AIRR. *International Journal of Production Economics*, *179*, 130–140. http://doi.org/10.1016/j.ijpe.2016.05.024

Darcovich, K., Henquin, E. R., Kenney, B., Davidson, I. J., Saldanha, N., & Beausoleil-Morrison, I. (2013). Higher-capacity lithium ion battery chemistries for improved residential energy storage with micro-cogeneration. *Applied Energy*, *111*, 853–861. http://doi.org/10.1016/j.apenergy.2013.03.088

Divya, K. C., & Østergaard, J. (2009). Battery energy storage technology for power systems-An overview. *Electric Power Systems Research*, *79*(4), 511–520. http://doi.org/10.1016/j.epsr.2008.09.017

Dunn, B., Kamath, H., & Tarascon, J.-M. (2011). Electrical Energy Storage for the Grid: A Battery of Choices. *Science*, *334*(6058), 928–935. http://doi.org/10.1126/science.1212741

Fitzgerald, G., Mandel, J., Morris, J., & Touati, H. (2015). The Economics of Battery Energy Storage: how multi-use, customer-sted batteries deliver the most services and value to customers and the grid, (October), 41. Retrieved from https://www.rmi.org/Content/Files/RMI-TheEconomicsOfBatteryEnergyStorage-FullReport-FINAL.pdf

Feibel, J., B. (2003). Investment Performance measurement. *John Wiley & Sons, Inc.* ISBN: 0-471-26849-6

Friedman, B., Margolis, R., & Seel, J. (2016). Comparing Photovolatic (PV) Costs and Deployment Drivers in the Japanese and U.S. Residential and Commercial Markets. *National Renewable Energy Laboratory.* Technical Report NREL/TP-6A20-60360. Contract No. DE-AC36-08GO28308.

Gordon, J. M. (1987). Optimal sizing of stand-alone PVsolar power systems. *Solar Cells*, *20*(4), 295–313. http://doi.org/10.1016/0379-6787(87)90005-6

Gordon, L. A., & Loeb, M. P. (2002). Return on information security investments: Myths vs. Realities. *Strategic finance*, *84*(5), 26-31.

Graebig, M., Erdmann, G., & Röder, S. (2014). Assessment of residential battery systems (RBS): profitability , perceived value proposition , and potential business models. In *37th IAEE International Conference* (Vol. 25, pp. 1–15). Retrieved from http://www.usaee.org/usaee2014/submissions/OnlineProceedings/Markus Graebig et al_Online Proceedings Paper_IAEE New York 2014_v05 final.pdf

Hahn, E. (2014). The Japanese Solar PV Market and Industry -Business Opportunities for European Companies-, (November), 48. Retrieved from https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwjVsMjH6onKAhUEOxQKHSAqDwIQFggfMAA&url=http%3A%2F%2Fwww.eu-japan.eu%2Fsites%2Feu-japan.eu%2Ffiles%2Freports%2FMINERVA%2FPVinJapan_Report_Minerva%2520Fellow.pdf&usg=

Hashimoto, T., Kawamata, T., Shimada, K. (2015). Commencement of Operation of Large-Scale Battery Energy Storage System for Nishi-Sendai Substation of Tohoku Electric Power Co., Inc. Toshiba Review, 70(9), 45-48. Retrieved from https://www.toshiba.co.jp/tech/review/2015/09/70_09pdf/f05.pdf

Hayakawa, M. (2015). "Shin kisei kijyun to genpatsu saikadou" [New regulations and the restart of nuclear power plants]. News Letter No.88 *Citizens' Alliance for Saving the Atmosphere and the Earth.* Retrieved from http://casaweb.html.xdomain.jp/casa/2/letter/88.8.pdf (in Japanese)

Hoppmann, J., Volland, J., Schmidt, T. S., & Hoffmann, V. H. (2014). The economic viability of battery storage for residential solar Photovolatic systems - A review and a simulation model. *Renewable and Sustainable Energy Reviews*, *39*, 1101–1118. http://doi.org/10.1016/j.rser.2014.07.068

Hosoe, N. (2006). The deregulation of Japan’s electricity industry. *Japan and the World Economy*, *18*(2), 230–246. http://doi.org/10.1016/j.japwor.2004.07.002

Huang, Y. H., & Wu, J. H. (2007). Technological system and renewable energy policy: A case study of solar photovoltaic in Taiwan. *Renewable and Sustainable Energy Reviews*, *11*(2), 345–356. http://doi.org/10.1016/j.rser.2004.12.004

IEA PVPS. (2016). *2015 Snapshot of Global Photovoltaic Markets*, 2016 Edition (Report No. Report IEA PVPS T1-29:2016). Retrieved from http://www.iea-pvps.org/fileadmin/dam/public/report/PICS/IEA-PVPS_-__A_Snapshot_of_Global_PV_-_1992-2015_-_Final_2_02.pdf

IEA-RETD. (2014). *Residential Prosumers - Drivers and policy options (Re-Prosumers).* Retrieved from http://iea-retd.org/wp-content/uploads/2014/06/RE-PROSUMERS_IEA-RETD_2014.pdf

Iga, A., Yamaguchi, M., Yokoyama, S., Sueda, O., Yoshii, K., & Kaneko, T. (2004). Study of the Merit of Battery Combined Photovoltaic Generation System for Residential House (2). *IEEJ Transactions on Power and Energy*, *124*(10), 1224–1230. http://doi.org/10.1541/ieejpes.124.1224

International Electrotechnical Commission. (2011). Electrical Energy Storage. *Electrical Energy Storage White Paper*, *39*, 11–12. http://doi.org/10.1016/j.icrp.2009.12.007

International Energy Agency (IEA). (2015). Enery Balances of OECD countries (2015 edition). France: *International Energy Agency.*

Intergovernmental Panel on Climate Change (IPCC). (2014). Summary for Policymakers. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32.

IRENA. (2015). Battery storage for renwables: Market status and technology outlook. *IRENA.* Retrieved from http://www.irena.org/documentdownloads/publications/irena_battery_storage_report_2015.pdf

IRENA. (2016). *REmap: Roadmap for a Renewable Energy Future*, 2016 Edition. Retrieved from www.irena.org/remap

Iwata, M. (2015). Japan CO2 Emissions Worst on Record. *The Wall Streat Journal.* Retrieved from http://blogs.wsj.com/japanrealtime/2014/11/17/japan-co2-emissions-worst-on-record/

Japan Business Publishing Co., Ltd. (n.d.). "Chikudenchi kanren no hojyokin" [Subsidies for a battery storage system]. Retrieved from https://www.kankyo-business.jp/subsidy/accumulator/ (in Japanese)

Japan Photovolatic Energy Association (JPEA). (2015). "Taiyoukou hatsuden no genjyou to tenbou" [Current status and forecast of photovaltic generation]. [PDF slides]. Retrieved from http://www.jpea.gr.jp/pdf/150219_deployment.pdf (in Japanese)

Japan Photovolatic Enegy Association (JPEA). (n.d.) "*Heisei 25 nenndono jyutaku you taiyouou hatsuden dounyu shienn hojyokin no gaiyouni tsuite*" [*Information on the subsidy for residential photovoltic generation in 2013*]. [Pamphlet]. N.P (in Japanese)

Kaneko, K. (2016). "Saiene Chikudenchi Project Saizensen. Semaru taiyoukou he no shutsuryokuyokusei? Kyuden ga oogata chikudenchi de kaihisaku" [At the forefront of renewable energy battery storage projects. Closing in on the output suppression of PV. Kyushu Electric introduced a workaround plan by large-scale batterries]. *Nikkei Business Publications, Inc.* Retrieved from http://techon.nikkeibp.co.jp/atcl/feature/15/415282/112100013/

Kaneko, K. (2014). "Kokunai panel maker no hinshutsu senryaku" [Strategy on the quality control of PV panels by domestic panel manufactures]. *Nikkei Business Publications, Inc.* Retrieved from http://techon.nikkeibp.co.jp/article/FEATURE/20140123/329440/

Kantor, I., Rowlands, I. H., Parker, P., & Lazowski, B. (2015). Economic feasibility of residential electricity storage systems in Ontario, Canada considering two policy scenarios. *Energy and Buildings*, *86*, 222–232. http://doi.org/10.1016/j.enbuild.2014.10.022

Kaushal, N. (2015). NPV vs IRR. *Wall Street Mojo.* Retrieved from http://www.wallstreetmojo.com/npv-vs-irr/

Khaligh, A., & Li, Z. (2010). Battery, ultracapacitor, fuel cell, and hybrid energy storage systems for electric, hybrid electric, fuel cell, and plug-in hybrid electric vehicles: State of the art. *IEEE Transactions on Vehicular Technology*, *59*(6), 2806–2814. http://doi.org/10.1109/TVT.2010.2047877

Kousksou, T., Bruel, P., Jamil, A., El Rhafiki, T., & Zeraouli, Y. (2014). Energy storage: Applications and challenges. *Solar Energy Materials and Solar Cells*, *120*(PART A), 59–80. http://doi.org/10.1016/j.solmat.2013.08.015

KYOCERA Coporation. (n.d.). "Lithium-ion chikuden system III・IV shousai shiyou" [Lithium-ion storage systems III・IV detail specs]. *KYOCERA corporation*. Retrieved from http://www.kyocera.co.jp/lithium/storage3/storage3_specs.html (in Japanese)

Lazou, A. A., & Papatsoris, A. D. (2000). Economics of PVstand-alone residential households: A case study for various European and Mediterranean locations. *Solar Energy Materials and Solar Cells*, *62*(4), 411–427. http://doi.org/10.1016/S0927-0248(00)00005-2

Liu, G., Rasul, M. G., Amanullah, M. T. O., & Khan, M. M. K. (2012). Techno-economic simulation and optimization of residential grid-connected PV system for the Queensland climate. *Renewable Energy*, *45*, 146–155. http://doi.org/10.1016/j.renene.2012.02.029

Maeda , N., Schmidt, G., N., & Moroi, R. (2011). Feed-in Tariff Act for Renewable Energy. Cross Border Newsletter. *Nishimura & Asahi.* Retrieved from https://www.jurists.co.jp/ja/topics/docs/newsletter_201112_cb.pdf

Mulder, G., Ridder, F. De, & Six, D. (2010). Electricity storage for grid-connected household dwellings with PV panels. *Solar Energy*, *84*(7), 1284–1293. http://doi.org/10.1016/j.solener.2010.04.005

Matsuki, T. (2016). "Kateiyou chiku denchi kunino hojyokin tsukiri. Honkaku fukyu he kosutonokabe wo yabureruka" [The end of a subsidy program for the residential battery storage systems. Is it possible to brake the wall of cost?]. *NIKKAN KOGYO SHIMBUN,LTD.* Retrieved from http://newswitch.jp/p/3709 (in Japanese)

Meridian International Research. (2005). Retrieved from http://www.meridian-int-res.com/Projects/Zebra_Pages.pdf

Ministry of Agriculture, Forestry and Fisheries (MAFF). (n.d.). "Kanmatsu shiryou: Jigyousei (Taiyoukou hatsuden) kentou sheet no riyouhou" [Appendix: Instructions on how to conducet a feasibility study on Photovolatic generation]. *Ministry of Agriculture, Forestry and Fisheries (MAFF).* Retrieved from http://www.jfa.maff.go.jp/test/keikaku/pdf/kanmatusitoriyouhou.pdf (in Japanese)

Ministry of Economy, Trade and Industry (METI). (2014). "Enerugi jyousei ni tsuite" [Overview of Japan's energy situation]. *Ministry of Economy, Trade and Industry (METI)*. Retrieved from http://www.meti.go.jp/committee/sankoushin/sangyougijutsu/chikyu_kankyo/yakusoku_souan_wg/pdf/001_05_01.pdf (in Japanese)

Ministry of Economy, Trade and Industry (METI). (2011). Feed-in Tariff Scheme for Renewable Energy. *Ministry of Economy, Trade and Industry (METI).* Retrieved from http://www.meti.go.jp/english/policy/energy_environment/renewable/pdf/summary201109.pdf

Ministry of Economy, Trade and Industry (METI). (2015). Report on Analysis of Generation Costs, Etc. for Subcommittee on Long - term Energy Supply - Demand Outlook. *Power Generation Cost Analysis Working Group. Ministry of Economy, Trade and Industry (METI).* Retrieved from http://www.meti.go.jp/english/press/2015/pdf/0716_01b.pdf

Ministry of Economy, Trade and Industry (METI). (2015). "Teichiyou chikudenchi no kakaku teigen scheme" [Scheme on the cost reduction of standalone type battery storage systems]. *Ministry of Economy, Trade and Industry (METI).* Retrieved from http://www.meti.go.jp/committee/kenkyukai/energy_environment/energy_resource/pdf/005_08_00.pdf (in Japanese)

Nair, N. K. C., & Garimella, N. (2010). Battery energy storage systems: Assessment for small-scale renewable energy integration. *Energy and Buildings*, *42*(11), 2124–2130. http://doi.org/10.1016/j.enbuild.2010.07.002

Naumann, M., Karl, R. C., Truong, C. N., Jossen, A., & Hesse, H. C. (2015). Lithium-ion battery cost analysis in PV-household application. *Energy Procedia*, *73*, 37–47. http://doi.org/10.1016/j.egypro.2015.07.555

New Energy and Industrial Technology Development Organization (NEDO). (2014). White paper on renewable energy. Challenges and prescription for enhancing the spread of reneable energy. *Morikita Publishing Co., Ltd.*

Nikkei. (2016). Japan's solar power feed-in tariff to fall 20% or more in 3 years. *Nikkei Inc.* Retrieved from http://asia.nikkei.com/Politics-Economy/Policy-Politics/Japan-s-solar-power-feed-in-tariff-to-fall-20-or-more-in-3-years

NGK INSULATORS, LTD. (n.d.). Corporate Profile. *NGK INSULATORS, LTD.* Retrieved from http://www.ngk.co.jp/english/about/publication/pdf/company_eng.pdf

NGK INSULATORS, LTD. (n.d.). Sodium Sulphur Battery, Energy Storage System. *NGK INSULATORS, LTD.* Retrieved from https://www.ngk.co.jp/nas/

Nuclear Energy Institute. (2017). Japan Nuclear Update. *Nuclear Energy Institute.* Retrieved from https://www.nei.org/News-Media/News/Japan-Nuclear-Update

O'Connor, R. (2013). Top 10 reasons to invest in renewable energy projects. *Blue & Green Tomorrow*. Retrieved from http://blueandgreentomorrow.com/features/top-10-reasons-to-invest-in-renewable-energy-projects/

OECD. (2013). OECD Economic Surveys: Japan 2013, *OECD* Publishing. http://dx.doi.org/10.1787/eco_surveys-jpn-2013-en

Panasonic Eco Solutions Canada Inc. (n.d.) *Residential Energy Storage Solutions.* Retrieved from https://panasonic.ca/brochures/EN/eco-solutions/ecosolutions_brochure_en.pdf

Ramirez, R., Mukherjee, M., Vezzoli, S., & Kramer, A. M. (2015). Scenarios as a scholarly methodology to produce "interesting research." *Futures*, *71*, 70–87. http://doi.org/10.1016/j.futures.2015.06.006

Renewable Energy Policy Network for the 21st Century. (2016). "Renewables 2016: Global Status Report. *Renewable Energy Policy Network for the 21st Century.* Retrieved from http://www.ren21.net/wp-content/uploads/2016/05/GSR_2016_Full_Report_lowres.pdf

Renewable Energy Policy Network for the 21st Century. (2015). "Renewables 2015: Global Status Report." *Renewable Energy Policy Network for the 21st Century.* Retrieved from http://www.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015_Onlinebook_low1.pdf

Shil, N. C. (2009). Performance Measures: An Application of Economic Value Added. *International Journal of Business and Management*, *4*(3), 169–177. http://doi.org/10.5539/ijbm.v4n3p169

Shimada, T. & Kurokawa, K. (2006). Grid-Connected PVSystems With Battery Storages Control Based on Insolation Forecasting Using Weather Forecast. *Renewable Energy*, 228–230. Retrieved from http://www.kurochans.net/paper/Re2006/shimada.pdf

Solxsell. (2016). "Taiyoukou hatsuden no taiyou nensuu・jyumyou. Solar Panal no keinen rettuka to dou mukiauka" (Life of PV systems. How to deal with a time-related deterioration of PV panles). *Solxsell.* Retrieved from https://solsell.jp/blog/1083/ (in Japanese)

Sony Energy Devices Corporation. (2016). History. *Sony Energy Devices Corporation.* Retrieved from http://www.sonyenergy-devices.co.jp/en/outline/history.php

Study Group for Enhancing Photovolatic Generation Competition. (2016). "Taiyoukou hatsuden kyousouryoku kyouka kenkyukai houkokusho" [Enhancing photovolatic generation competition]. *Ministry of Economy, Trade and Industry (METI).* Retrieved from http://www.meti.go.jp/committee/chotatsu_kakaku/pdf/025_s01_00.pdf (in Japanese)

Sustainable Energy For All.(n.d.). Sustainable Development Goal 7 - Post 2015 Sustainable Development Agenda. Retrieved from http://www.se4all.org/sdg7

The Asahi Shimbun Company. (2016). "Genpatsu saikadou hantai 57% Asahi Shinbun yoron chosa" [57% of respondants opposed to the restart of nuclear power plants]. *The Asahi Shimbun Company.* Retrieved from http://www.asahi.com/articles/ASJBK4H0XJBKUZPS001.html (in Japanese)

The Federation of Electric Power Companies of Japan (FEPC). (2016). Nuclear Power Plants in Japan. *The Federation of Electric Power Companies of Japan (FEPC).* Retrieved from http://www.fepc.or.jp/english/nuclear/power_generation/plants/

The Federation of Electric Power Companies of Japan (FEPC). (n.d.). "Denryoku tokei jyouhou" [Statistical data on electricity]. *The Federation of Electric Power Companies of Japan (FEPC).* Retrieved from http://www5.fepc.or.jp/tok-bin/kensaku.cgi

The Kansai Electric Power Company (KEPCO). (2017). "Enerugi no best mix" [Best Energy Mix]. The Kansai Electric Power Company, Incorporated (KEPCO). Retrieved from http://www.kepco.co.jp/energy_supply/energy/nuclear_power/nowenergy/bestmix.html (in Japanese)

The Kansai Electric Power Company (KEPCO). (n.d.). *"Happy e time denki ryoukin no goannai" [About happy e time plan].* [PDF file]. Japan: The Kansai Electric Power Company, Incorporated (KEPCO). Retrieved from https://kepco.jp/~/media/Files/KepcoJp/Customer/pdf/ryokin/menu/hapie_201706.ashx?la=ja-JP (in Japanese)

The Purchase Price Calculation Committee. (2016). "Heisei 28 nendo choutatsu kakaku oyobi choutatsu kikan ni kansuru iken" [Opinions on FY2016's purchase price and purchase periods]. *Ministry of Economy, Trade and Industry (METI).* Retrieved from http://www.meti.go.jp/committee/chotatsu_kakaku/pdf/report_005_01_00.pdf (in Japanese)

The Sankei Shimbun & Sankei Digital. (2016). "Kadou 33 nen no Tsubosaka dera no taiyou kou hatsuden no seinou wa? San nou ken ga chousa" [The performance study of PV panels operating 33 years at Tsubosaka dera]. Retrieved from http://www.sankei.com/region/news/160423/rgn1604230064-n1.html (in Japanese)

The Sankei Shimbun & Sankei Digital. (2016). "Sharp no lithium chikudenchi hanbai mokuhyou no 1/3 ni. Sakunendo shijyou zentaiga nobinayami. Shin shouhin de makikaeshi he" [Sharo only recorded 1/3 of the target sales]. Retrieved from http://www.sankei.com/west/news/160404/wst1604040108-n1.html (in Japanese)

The U.S. Energy Information Administration (EIA). (2015). Japan restarts first nuclear reactor under new safety rules. U.S. Department of Energy. Retrieved from http://www.eia.gov/todayinenergy/detail.cfm?id=22472

The U.S. Energy Information Administration (EIA). (2015). Japan. U.S. Energy Information Administration. U.S. Department of Energy. Retrieved from http://www.eia.gov/beta/international/analysis_includes/countries_long/Japan/japan.pdf

Thompson, S, N. (2015). Japan restarts first nuclear reactor under new safety rules. *The U.S. Energy Information Administration (EIA). U.S. Department of Energy.* Retrieved from http://www.eia.gov/todayinenergy/detail.cfm?id=22472

Ueda, Y., Kurokawa, K., Itou, T., Kitamura, K., Akanuma, K., Yokota, M., … Morimoto, A. (2008). Advanced analysis of grid-connected PV system's performance and effect of batteries. *Electrical Engineering in Japan*, *164*(1), 21–33. http://doi.org/10.1002/eej.20660

Ueda, Y., Kurokawa, K., Itou, T., Kitamura, K., Akanuma, K., Yokota, M., … Morimoto, A. (2006). Performance analyses of battery integrated grid-connected residential PV systems. In *21st European PVSolar Energy Conference Proceedings* (pp. 2580–2584). Dresden, Germany. Retrieved from http://www.kurochans.net/paper/21th_EUPVSEC/EU_PVSEC_21th_Ueda.pdf

United Nations Framework Convention on Climate Change (UNFCCC). (2015). Submission of Japan's Intended Nationally Determined Contribution (INDC). Retreived from http://www4.unfccc.int/submissions/INDC/Published%20Documents/Japan/1/20150717_Japan's%20INDC.pdf

Weniger, J., Bergner, J., Tjaden, T., & Quaschning, V. (2014). Economics of residential PV battery systems in the self-consumption age. In *29th European PVSolar Energy Conference and Exhibition* (pp. 2936–2938). Retrieved from http://pvspeicher.htw-berlin.de/wp-content/uploads/2014/04/EUPVSEC-2014-Economics-of-Residential-PV-Battery-Systems-in-the-Self-Consumption-Age.pdf

Weniger, J., Tjaden, T., & Quaschning, V. (2014). Sizing of residential PV battery systems. *Energy Procedia*, *46*, 78–87. http://doi.org/10.1016/j.egypro.2014.01.160

Willis, J. W., & Jost, M. (2007). *Foundations of qualitative research: Interpretive and critical approaches.* Sage.

Yamaguchi, M., Iga, A., Ishihara, K., Wada, D., Yoshii, K., & Sueda, O. (2003). Study for merit of battery combined PVgeneration system for residential house. *IEEJ Transactions on Power and Energy*, *123*, 402-411.

Yamaguchi, M. (2013). *Towards efficient redesigning of Japan's FIT scheme on Renewable Energy.* In the society for Environmental Economics and Policy Studies of Japan Conference.

Yamazaki, T. (2015). Japan's Electricity Market Reform and Beyond. *Electricity Market Division, Electricity Market Reform, Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry (METI).* Retrieved from https://www.iea.org/media/workshops/2015/esapplenaryjuly2015/Yamazaki.pdf

Yoshida, A., Sato, T., Amano, Y., & Ito, K. (2016). Impact of electric battery degradation on cost- and energy-saving characteristics of a residential PVsystem. *Energy and Buildings*, *124*, 265–272. http://doi.org/10.1016/j.enbuild.2015.08.036

Yoshino, K. (2015). Japan's Current Nuclear Energy Policy. Japan's Current Nuclear Energy Policy. Energy and Environmental Policy. *Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry (METI).* Retrieved from https://www.iaea.org/NuclearPower/Downloadable/Meetings/2015/2015-10-05-10-08-NIDS/Session1/Session_1-2-1_Mr.Yoshino_IAEA_TM_in_FukuiJapans_Current_Nuclear_Energy_Policy.pdf

Yoza, A., Yona, A., Senjyu, T., & Funabashi, T. (2014). Optimal capacity and expansion planning methodology of PV and battery in smart house. *Renewable Energy*, *69*, 25–33. http://doi.org/10.1016/j.renene.2014.03.030

Zero Home Corporation. (n.d.). Kyocera 7.2kWh lithium ion battery systems. *Zero Home Corporation.* Retrieved from http://www.taiyoko-kakaku.jp/product/kyocera-batt (in Japanese)