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An Economic and Environmental Optimization Model for Household Energy-Saving Upgrades in Different Regions of Japan

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Major in System Design and Management
### SUMMARY OF MASTER’S DISSERTATION

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**Title**
An Economic and Environmental Optimization Model for Household Energy-Saving Upgrades in Different Regions of Japan

**Abstract**

Responding to global warming problems, Japanese government has set the target to reduce CO$_2$ emissions by 39% in 2030 compared with 2013 in the residential sector. Therefore, it is essential to diffuse energy-saving houses, and the introduction of Photovoltaics (PV) is assumed as a residential energy-saving upgrade.

However, when PV is installed into households, the electric power company has to construct thermal power stations to deal with surplus power. Consequently, CO$_2$ emission increases. The implementation of household battery systems can solve this problem but causes the increase of household cost.

Therefore, in order to accelerate energy-saving upgrades, it is important to clarify how large should the capacity of battery be to achieve the lowest total cost. The total cost includes household cost, electric power company cost and government cost. The former two are from economic aspects, and the latter one is from environmental aspect of CO$_2$ emission. The purpose of this research is to make suggestions about the best capacity of battery where the lowest total cost can be achieved.

This research developed an economic and environmental optimization model for energy-saving upgrades in households. The requirements of multi-stakeholders (households, government and electric power companies), regional differences and equipment subsidy are included in the model, which are the originalities of this research. By inputting open data from the government into the model, the simulations of present scenario (2017), and future scenarios (2025&2030) were performed.

The simulation results of present scenario show that when PV and battery systems are installed into households, household cost decreases, but CO$_2$ emission and electric power company cost increase in all regions. It does not suggest installing PV or batteries.

On the other hand, the simulation results of future scenarios show that when PV and battery systems are installed into households, household cost, CO$_2$ emission and total cost decrease in all regions. The best capacity of battery is suggested for each region.

**Key Word (5 words)**
CO$_2$ emission, Energy Saving, Photovoltaics (PV), Battery, Simulation
1. Introduction

1.1 Research Background

1.1.1 Global Warming

The Earth’s climate is changing. Temperatures are rising. Since 1901, global average surface temperature has been rising at an average rate of 0.15°F per decade [1]. Snow and rainfall patterns are shifting, and more extreme climate events like heavy rainstorms are already happening. In addition, it is predicted that these observed changes are likely to become more frequent and more intense according to scientific studies. The rising levels of greenhouse gases in atmosphere caused by human activities are the main reasons of global warming.

Greenhouse gases warm the Earth by absorbing energy and slowing the rate at which the energy escapes to space [2]. Greenhouse gases include Carbon Dioxide (CO₂), Methane (CH₄), Nitrous Oxide (N₂O), and Fluorinated gases. CO₂ takes up 65% that accounts for the largest proportion [3]. CO₂ can be emitted from direct human-induced impacts on forestry and other land use, such as through deforestation and land clearing for agriculture. The primary source of CO₂ is fossil fuel use. Global energy-related CO₂ emissions are shown in Figure 1.1. From Figure 1.1, it can be seen that CO₂ emissions have been increasing.
In Japan, CO₂ emissions account for 92.4% of greenhouse gas emissions. And 86.5% of CO₂ emissions come from energy consumption [5]. Figure 1.2 shows the trends in CO₂ emission and removals from 1990 to 2016 in Japan. Although in some years like 2009, CO₂ emission was lower than years before and after, it shows increasing trend from the whole picture. Furthermore, from 2011 to 2014, CO₂ emission increased a lot and it reached a record high in 2014. The reason is that under the huge effect of the Great East Japan Earthquake in March 2011, the composition ratio of thermal power generation has increased, which means the dependency on fossil fuel burning has gone up. Figure 1.3 shows the changes of composition ratios of power supply before and after the Great East Japan Earthquake. From Figure 1.3, it is obvious that nuclear energy decreased to 0, and ratios of coal, petroleum and LNG increased a lot. Therefore, it can say that global warming has intimate relation with energy.
Figure 1.2 Trends in CO₂ Emission and Removals in Japan

(Made by Author Based on Reference [6])

Figure 1.3 Composition Ratios of Power Supply Before and After

March 2011 Great East Japan Earthquake

(Made by Author Based on Reference [7])
In Japan, in order to realize Japan’s Intended Nationally Determined Contribution (INDC) and correspond to the Paris Agreement, CO\textsubscript{2} emission reduction targets have been set. It aims to reduce 26% of CO\textsubscript{2} emission by fiscal year (FY) 2030 and 80% by FY 2050 compared to FY 2013. For residential sector, it intends to decrease 39% by FY 2030 compared to FY 2013 [8] [9]. In addition, according to Long-term Energy Supply and Demand Outlook from Ministry of Economy, Trade and Industry, a level of 22~24% renewable energy in power supply in 2030 is aimed for the realization of low carbon society [10]. Thereby, the expend of renewable energy is expected to deal with global warming problems.

1.1.2 Energy Security

The relation between serious global warming and energy, and the promotion of renewable energy as one of the solutions are introduced in last section. In this section, the urgency of expanding renewable energy in Japan is explained from the view of energy security.

Japan is not blessed with fossil resources and depends on imports of almost all of its energy resources. Around 86% of crude oil in Japan is dependent on Middle East countries like Saudi Arabia and United Arab Emirates. For coal and LNG, they are mostly imported from other countries as well, such as Australia [11]. Figure 1.4 shows the energy self-sufficiency of OECD (Organization for Economic Cooperation and Development) countries in 2017 [12]. It can be seen that Japan has extremely low energy self-sufficiency compared with other countries. Japan’s energy self-sufficiency (including nuclear power) in 2010 before the Great East Japan Earthquake was about 20%, but after the Great East Japan Earthquake, it decreased to only 9% in 2017 due to the closure of the nuclear power plants, etc. [13]. The energy supply structure in Japan is vulnerable.
Furthermore, as for global trends, the main source of energy demand is shifting from developed to developing countries like China and India. As a result, fierce competition for resources in emerging countries is occurring around the world [13]. Together with the fluctuating resource prices, these trends have vital impact on energy security of Japan. Therefore, it is urgent for Japan to improve energy supply structure by expanding renewable energy existing in Japan such as solar power, wind power, geothermal energy, etc.

1.1.3 Energy-Saving House

In Section 1.1.1, it mentions that Japan aims to reduce 39% of CO\textsubscript{2} emission in 2030 compared with 2013 for residential sector. In addition, as shown in Figure 1.5, energy consumption in residential sector had increased to 2.9 fold from 1973 to 2014 while 1.3 fold of rise occurred in all sectors including transport, commercial, residential and industrial sectors [14]. Therefore, it is important to conduct energy saving countermeasures in residential sector, and one of the ways is to spread energy-saving houses.
Nowadays, there are mainly three ways to conduct energy-saving upgrades. First way is to improve thermal insulation performance like replacing windows and changing the material of wall, floor, etc. Second way is to implement highly efficient domestic electrical appliances such as introducing highly efficient air conditioner, hot water supply equipment, lighting facilities, etc. In Japan, the Top Runner Program is established as a countermeasure to deal with ongoing energy consumption increases in residential sector. It aims to improve the energy consumption efficiency of appliances including air conditioners, lighting equipment, TV sets, electric refrigerators, etc. in the residential sector [14]. Third way is to install energy-related systems like Photovoltaic (PV), battery, etc. All of three energy-saving upgrades above are inevitable for ZEH (Net Zero Energy House), which is promoted by Japan’s government [15].

Since new-constructed houses in Japan have to meet energy conservation regulations [16], only existing houses are targets in this research. Moreover, as the promotion of renewable energy is the ultimate way to improve Japan’s energy problem explained in the last two sections, the third way of installing energy-related systems is considered in this research.

Figure 1.5 Status of Energy Consumption in Japan [14]

1.1.4 Photovoltaic

As one kind of renewable energy, solar energy is widely available all over the world. It can not only contribute to reducing dependence on energy imports, but also
improving security of power supply, for it gets rid of fuel price risks and constraints [17]. It can be seen that promoting solar energy is suitable for Japan’s current situation. Solar energy can converse sunlight into different usable energy forms such as solar photovoltaic (hereafter, solar photovoltaics is PV), solar thermal electric power and solar heating and cooling. PV dominates renewable capacity growth in the next six year [18]. PV systems directly convert solar energy into electric power. In 2017, global power generated by PV represents around 2% of global power output [19].

Figure 1.6 shows the number of houses with PV system installed in Japan. Although from Figure 1.6, the introduction of residential PV system has been increasing sharply recently, the number of houses with PV system only accounts for 7.2% of total number of houses [20]. One of the reasons is the high installation cost of PV. But in the coming years, it is predicted that average PV prices will continue to decline as competition increases and manufacturing capacity grows in China and South East Asia [21]. Another issue of PV system is that as PV generates power from sunlight, power output is limited to times when the sun is shining, which means it is unstable power supply. Therefore, changes of existing electric power system are needed to deal with unstable electric power generated by PV.

![Figure1.6 Number of Houses with PV installed in Japan](image-url)
1.1.5 Surplus Power Problems

With the wide spread of PV system introduced into houses, it is necessary to consider the countermeasures to deal with surplus electric power that is generated by PV but cannot be fully consumed by households. Figure 1.7 shows the relation between the amount of electric power generated by PV and household electric power consumption per hour [22]. Here, 4kW PV system is installed into the house. From Figure 1.7, the amount of household electric power consumption is low during daytime, but it increases a lot at night. On the contrary, the amount of electric power generated by PV is high around noon. Therefore, during day time, since electric power generated by PV cannot be fully consumed in the house, surplus power occurs. In Japan, feed-in tariff (FIT) policy has been phased out since 2012. Under FIT policy, household can sell surplus power generated by PV to electric power company at FIT price, which is 30 Yen/kWh in 2017 [23]. However, with unstable power purchased, electric power company has to stabilize power system by running backup battery which relies on thermal power generation. Consequently, CO₂ emission increases that goes against the introduction purpose of PV system.

Considering above issues, there are three surplus power countermeasures according to reference [22]. Firstly, transform the surplus power into hydrogen in electric power company. However, hydrogen technology is not well developed now. Secondly, instead of selling surplus power to electric power company, send surplus power to other places where electric power is not enough. In this case, the constructions of smart grid and macro grid are need. But under current technology and regulation, it is impossible. Finally, store surplus power into battery system, which is realizable with existing technologies. In this research, household battery system is considered as the solution to surplus power generated by PV.
Since surplus electric power generated by PV is either sold to electric power company or stored in battery by installing battery system into the house. Depending on which one to choose, for household, government and electric power company who are considered as stakeholders in this research, merits and demerits differ. Table 1.1 shows the merits and demerits of selling and storing surplus power respectively for every stakeholder. Stakeholders assumed in this research are stated in details in Chapter 2.

In Table 1.1, merits in black and demerits in red are listed. When surplus power is sold to the electric power company, the household can get profits under FIT price. However, since unstable electric power flows into the system, the electric power company has to establish backup battery to deal with the unstable power, which causes extra cost. Besides, as backup battery is thermal power generation equipment, the running of backup battery emits CO$_2$. Because the government commits to reducing CO$_2$ emission in order to prevent global warming, the selling of surplus power is against the government’s interest. On the other hand, if surplus power is chosen to be stored in the battery system, the household needs to install the battery system, whose price is quite high in current market. Thus, the household has to pay for the price. In addition, without unstable surplus power flows to the system, the electric power company can remain stable power, and no CO$_2$ emits from the backup battery system that can be viewed as the government’s merit.

From Figure 1.1, it is obvious that by selling surplus power to the electric power company, or by storing it in the house, the merits and demerits for every stakeholder differ. Under this situation, whether to sell or store surplus power is especially related to...
the FIT price and the price of battery system, which are strongly affected by the development of PV and battery technologies.

Table 1.1 Merits and Demerits of Selling and Storing Surplus Power

<table>
<thead>
<tr>
<th>Surplus power</th>
<th>Household</th>
<th>Government</th>
<th>Electric Power Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sell</td>
<td>Profits</td>
<td>CO₂ emission</td>
<td>• Unstable electric power system</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• System stabilization cost</td>
</tr>
<tr>
<td>Store (battery)</td>
<td>High payment for battery</td>
<td>No CO₂ emission</td>
<td>Stable system</td>
</tr>
</tbody>
</table>

1.1.6 Technology Development and Region Differences

The future goals for household PV and the battery system are showed in the technology road maps [24] [25]. In the road maps, the functional and pricing goals are established. However, since the future goals for PV and the battery system are set separately, when both PV and the battery system are installed into a house with achieved technology goals, the economic and environmental aspects of the household have not been quantified. Although, PV and the battery system can be operated separately, the use of both of them in the future are getting more necessary. Therefore, in order to clarify the economic and environmental aspects of the household, technology development in the future cannot be ignored.

Furthermore, as explained in Section 1.1.4 that the amount of electric power output generated by PV is limited to times when the sun is shining, and it varies from the amount of solar irradiance. With the same capacity and efficiency of PV installed into houses in different regions, the household in the region with abundant sunlight can get more electric power generated by PV than the household in the region with less solar irradiance. Therefore, it can be considered that the economic and environmental effects of PV and battery system are different from region to region.
1.2 Research Purposes

As explained in Section 1.1 that under the background of global warming and energy security problems in Japan, it is important to install PV systems into households. However, when PV is introduced into households, the generated electric power that cannot be fully consumed by households is sold to electric power companies. At that time, electric power companies have to construct extra backup battery systems based on thermal power generation to stabilize the whole power system. Consequently, CO₂ emission and electric power company cost increase. The implementation of household battery systems can solve the surplus power problem, but households need to pay for the introduction price which is quite high currently. Therefore, in order to accelerate energy-saving upgrades, it is important to clarify that when PV is installed into households, how large should the capacity of battery be to achieve the lowest total cost. Here, the total cost includes household cost, electric power company cost and government cost, which are described in Chapter 3 in detail.

In this research, an economic and environmental optimization model is developed in order to minimize the total cost. By inputting open data from the government and other official organizations into the model, the simulations of present scenario (2017), and future scenarios (2025 & 2030) are performed. Based on simulation results, the optimal capacities of battery introduced into households are suggested in both current and future cases.

The purpose of this research is to make suggestions about the best capacity of battery for five regions in Japan, where the lowest total cost can be achieved.

1.3 Originality of Research

A variety of previous studies about residential PV and battery systems have been done. Three of them close to this research are described in the following.

In Ikezawa’s study [22], when PV was implemented in a household, the introduction of electrical vehicle was considered as the measure to deal with surplus electric power problems. The reductions of CO₂ emission, household cost and electric power company cost were quantitatively analyzed considering the requirements of three stakeholders (household, government and electric power company). In addition, technology development and changes of FIT in the future were considered as well.
However, when the household chooses between gasoline vehicles and electric vehicles, the initial cost does not make much difference compared with the initial cost of household batteries. Therefore, the household cost in this previous study and this thesis are in different levels. Furthermore, in this study, since the data of Yokohama City were assumed as the average values of the whole country, regional differences were not included.

In Nagai’s study [26], for the purpose of minimizing CO₂ emissions in residential area with power interchange in 2030, the introductions of PV, battery systems and highly efficient water heaters respectively, and combinations of at least two of them were taken into consideration. The reduction of CO₂ emissions was quantified in all scenarios. However, since households and the electric power company play important roles in power interchange, their interests and costs cannot be disregarded. In addition, regional differences were missing in this study as well.

In Weniger’s study [27], an economic assessment of residential PV battery systems in Germany was carried out in order to derive recommendations for their cost-optimal sizing. Long-term scenario was conducted as well considering the changes of FIT in the future. However, since the purpose of FIT policy is to accelerate investment in renewable energy technologies like PV, the environmental assessment reflecting CO₂ emissions is necessary. For residential PV battery systems, the view from the government’s side was missing.

In this research, both economic and environmental assessments of residential PV and battery system are implemented in 5 regions in Japan including Kyushu, Kansai, Kanto, Tohoku and Hokkaido regions. In the meanwhile, this research considers the costs of three stakeholders (household, the government and the electric power company), and equipment subsidy of PV and battery as well.

From the above, the originality of this research consists of three parts. Firstly, the interests of three stakeholders including the household, the government and the electric power company are considered when PV and the battery system are introduced into the house. Secondly, regional differences are included while analyzing the effects of these systems. Thirdly, it considers not only FIT, but also equipment subsidy of PV and battery.

This thesis is divided into eight chapters. Chapter 2 describes stakeholders considered in this research and their requirements. Chapter 3 describes the optimization model. Chapter 4 explains the inputs to the model and other preconditions in detail. Chapter 5 explains the how carbon tax is designed in this research. Chapter 6 shows the simulation results of present and future scenarios respectively, and analyzes all of them
by region. Chapter 7 discusses about the simulation results from the whole picture.
Chapter 8 shows the conclusions of this research by making suggestions to each region.
2. Stakeholders

2.1 Stakeholder Analysis

In order to consider multi-stakeholders, when PV and battery system are introduced into a house, all the stakeholders related are analyzed. Customer Value Chain Analysis (CVCA) is used for visualizing the interest relations among stakeholders. CVCA is showed in Figure 2.1.

In Figure 2.1, government, household, electric power company, battery maker and solar panel maker are listed as stakeholders. In addition, households are divided into households without any energy-related system, and households with PV system only or with both PV and battery systems. In Figure 2.1, if interest relations are involved with general households, arrows point the big frame which means general households. On the other hand, if interest relations are concerned with only households with PV or with PV and battery systems, arrows point the small frame.

From Figure 2.1, stakeholders considered in this research, whose interests are related to electric power, are cleared up. All households purchase electric power from electric power company. For households with PV system or with PV and battery systems, they can sell electric power to electric power company if surplus electric power is generated. Electric power company gets profits from households by providing them with electric power, and pays for surplus electric power based on FIT price. Government offers PV and battery subsidy to households, for the introduction of PV and battery systems benefits CO₂ emission reduction. Furthermore, solar panel maker and battery maker get profits by selling products to households. However, for makers, the purpose of providing households with products is to increase profits, and has nothing to do with the running ways of products in houses. Therefore, while considering the economic and environmental effects of PV and battery systems, makers are not included into the stakeholders in this research.
Figure 2.1 Customer Value Chain Analysis (Made by Author Based on Reference [22])
2.2 Stakeholder Requirements

In this Section, requirements of stakeholders explained in Section 2.1 are organized. Stakeholders considered in this research are household, government and electric power company. Requirements of every stakeholder are explained as below in the order of household, government and electric power company.

Firstly, household requirements are explained according to reference [28]. In reference [28], key buying factors of energy-saving facilities including PV system are analyzed by conducting questionnaires. According to the results, the most important factor of purchasing energy-saving facilities is related to running cost reduction. And the most vital factor of not introducing energy-saving facilities is about high initial cost. Therefore, it is assumed that households require decreasing cost involved with electric power consumption with PV system.

Secondly, there are greenhouse gas emission reduction targets in Japan, which are reducing 26% for the whole country, and 39% for household sector in 2030 compared with greenhouse gas emissions in 2013 [29]. In addition, the promotion of renewable energy contributes to CO\textsubscript{2} emission reduction [30]. Thus, for government, the requirements are to decrease CO\textsubscript{2} emission along with electric power consumption in households.

Finally, for electric power company, one of the requirements is to provide stable electric power according to the hearing from staff in Minami Souma Electrical Substation of Tohoku Electric Power Company. Furthermore, according to reference [22], purchased surplus electric power based on FIT is so unstable that extra thermal power generation is necessary to be constructed. Therefore, another requirement of electric power company is to reduce the extra system stabilization cost related to surplus electric power. In Table 2.1, all the requirements of stakeholders are listed.

<table>
<thead>
<tr>
<th>Stakeholders</th>
<th>Requirements</th>
</tr>
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<tbody>
<tr>
<td>Household</td>
<td>Reduce electric power charge</td>
</tr>
<tr>
<td>Government</td>
<td>Reduce CO\textsubscript{2} emission</td>
</tr>
<tr>
<td>Electric power company</td>
<td>Provide stable electric power</td>
</tr>
<tr>
<td></td>
<td>Reduce system stabilization cost dealing with surplus electric power</td>
</tr>
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</table>
3. Evaluation Model

3.1 Outline of Optimization Model

In this research, an economic and environmental evaluation model is built for houses with PV and battery system. Figure 3.1 shows the whole image of target house with PV set in the roof, and battery system installed. The following describes how electric power flows in the target house in Figure 3.1. Direct current generated by PV is transformed into alternating current that can be consumed in the house through power conditioner. Transformed alternating current is sent to every room by distribution board, and it is consumed by all kinds of domestic electrical appliances. Surplus power that cannot be fully used in the house is either stored into battery or sold to electric power company via electricity meter. Household can purchase electric power from electric power company as well. And it is also consumed by all domestic electrical appliances through distribution board. In Figure 3.1, although both PV and battery are introduced into the house, whether battery system is installed into the house or not depends on stakeholders requirements explained in Chapter 2. Therefore, variable related to whether battery is introduced or not is include in the model. If battery system is not suitable to be installed, by removing battery in Figure 3.1, it will be the whole image of target house.

![Figure 3.1 The Whole Image of Target House](image-url)
In order to apply the whole image of research target into evaluation model, Figure 3.2 shows the schematic of electric power flow based on Figure 3.1. Arrows in Figure 3.2 mean the directions of electric power’s flow. Symbol X2Y means electric power flows from X to Y. Every object is signified in different alphabet. H (House) means household. G (Grid) means electric power company. B (Battery) means battery. When the arrow points at battery, it means that battery is charging. When the arrow points from battery, it means that the electric power stored in battery is discharging. In addition, the arrows point from PV mean that electric power generated power is consumed by household, sold to electric power company and stored into battery. In this research, it is assumed that electric power generated by PV is in preference to be consumed by household (PV2H). The rest of electric power is either sold to electric power company (PV2G), or stored in battery (PV2B). The arrows point at household show that consumed electric power is from PV, battery and electric power company. As explained above, electric power generated by PV takes the priority to be consumed, and insufficient part is either purchased from electric power company, or from discharging of battery. The arrow points at electric power company is from PV only, which means it is possible to sell surplus power generated by PV to electric power company. In this research, it is assumed that electric power stored in battery cannot be sold to electric power company. The arrows point from electric power company to household and battery mean the purchase of electric power from electric power company. The same as explanation of Figure 3.2, when battery system is not installed into the house, by removing battery equipment and arrows pointing at and from battery in Figure 3.2, it will be the model target.

Figure 3.2 The Schematic of Electric Power Flow
In the evaluation model built in this research, by calculating the amount of electric power flowing among elements in Figure 3.2, economic cost and \( \text{CO}_2 \) emission from the house with PV and battery system installed are quantitatively analyzed. The way to calculate the amount of electric power flowing among elements is to solve optimization problem. For optimization problem, objective function, constraints and design variables are needed. In the evaluation model of this research, objective function is integrated indicates considering every stakeholder. And it is described in details in Section 3.3. Furthermore, the model built in this research is dynamic because the amount of electric power flowing among elements is changing every hour. Therefore, it is necessary to secure the consistency of electric power amount in every hour. In order to make sure of the consistency, constraints are set, which are explained in Section 3.4. In optimization problem, it is common to suppose variables, whose values are required from the solution of optimization problem, as design variables. Thus, in the model of this research, the amount of electric power flowing among elements is assumed as design variables.

Since multi-stakeholders are considered in this research, for multi-objective optimization problem, there are generally two ways to solve it [31]. The first way is to choose the most important evaluation criterion as the objective function, and change other evaluation criteria into constraints. The second way is to combine all the evaluation criteria into a new one. For example, by weighting each evaluation criterion, the sum of them is the new evaluation criterion. This method is called weighting coefficient.

In this research, weighting coefficient method is used to solve optimization problem. One evaluation indicator is made by firstly changing every stakeholder’s requirements into currency values as economic cost, and then integrating all of them.

Figure 3.3 shows the conceptual diagram of optimization model based on optimization problem designed in this research. In this model, inputs include characteristics values of PV and battery, constraints and preconditions. With these inputs, optimal amount of electric power flowing among elements can be get as outputs.
Figure 3.3 Conceptual Diagram of Optimization Model
3.2 Optimization Problem

In this research, mixed-integer linear programming (MILP) is used to solve the optimization problem. In this section, the way of using mixed-integer linear programming solver by MATLAB is described with an specific example [32].

Finds the minimum of a problem specified by

Objective function:

\[ \text{Minimize } f(x) \]

Constraints:

- \( x \) (intcon) are integers
- \( A \cdot x \leq b \)
- \( Aeq \cdot x = beq \)
- \( lb \leq x \leq ub \)

Syntax is

\[ x = \text{intlinprog}(f, \text{intcon}, A, b, Aeq, beq, lb, ub) \]

\( f \): Vector representing objective \( f' \cdot x \)
\( \text{intcon} \): Vector indicating variables that take integer values
\( A \): Matrix in linear inequality constraints
\( b \): Vector in linear inequality constraints
\( Aeq \): Matrix in linear equality constraints
\( beq \): Vector in linear equality constraints
\( lb \): Vector of lower bounds
\( ub \): Vector of upper bounds
For example, the following problem is under solved.

Objective function:

\[
\text{Minimize } f(x) = -3x_1 - 2x_2 - x_3
\]

Constraints:

\[
\begin{align*}
x_1, x_2 & \geq 0 \\
x_3 & \text{ binary} \\
x_1 + x_2 + x_3 & \leq 7 \\
4x_1 + 2x_2 + x_3 & = 12
\end{align*}
\]

In the command window of MATLAB, the inputs needed are shown in Figure 3.4. Write the objective function vector \( f \), vector of integer variables \( \text{intcon} \), the linear inequality constraints \( A, b \), the linear equality constraints \( Aeq, beq \), and the bound constraints \( lb, ub \). Then call \texttt{intlinprog} by \( x = \text{intlinprog}(f, \text{intcon}, A, b, Aeq, beq, lb, ub) \). The optimal objective value of \( f(x) \) and the optimal solutions of \( x_1, x_2, x_3 \) will automatically show in the same window, which is shown in Figure 3.5. It can be seen that when \( x_1 = 0, x_2 = 5.5, x_3 = 1 \), \( f(x) \) gest the minimum value of \(-12\).

```matlab
gf = [-3;-2;-1];
gintcon = 3;
gA = [1,1,1];
gb = 7;
gAeq = [4,2,1];
gbeq = 12;
glb = zeros(3,1);
gub = [Inf;Inf;1];
gx = intlinprog(f,gintcon,gA,gb,gAeq,gbeq,glb,gub)
```

Figure 3.4 Inputs in Command Window of MATLAB
In this research, the optimization problem is designed with the variables signifying the capacity of battery installed. The variables are limited as integers, and the optimization model designed uses mixed-integer linear programming.

### 3.3 Objective Function

This section describes objective function of the optimization problem designed in this research. Every stakeholder’s requirements are changed into currency value as economic cost firstly. Then by integrating all of them, an evaluation index is defined. Since economic cost varies from different views of point, it is necessary to define the scope of it. In this research, cost related to household electric power consumption, the purchase and selling of surplus power, and the installation and use phases of PV and battery system are within the scope. In Table 3.1, every stakeholder’s cost is listed for formularization. Since household can get profit by selling surplus power generated by PV, this part of profit is shown with ‘-‘ in Table 3.1. Electric power company is able to get electric power without generating it due to the purchase of surplus power from household. Therefore, it can be considered that electric power company is not only able to get that amount of electric power without any generation cost, but also get profits from it. Those profits for electric power company are called avoidable cost \([23]\). Avoidable cost is shown with ‘-‘ in Table 3.1 as well. Although electric power company needs to pay for the surplus power sold by household, it is not included into electric power company cost, because that amount of fee is collected as part of electric power charge from households.
Table 3.1 Cost of Every Stakeholder

<table>
<thead>
<tr>
<th>Household</th>
<th>Electric power charge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>the selling of surplus power</td>
</tr>
<tr>
<td></td>
<td>Introduction cost of PV</td>
</tr>
<tr>
<td></td>
<td>Introduction cost of battery</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Government</th>
<th>CO$_2$ emission from power generation in electric power company</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO$_2$ emission from power generation by PV</td>
</tr>
<tr>
<td></td>
<td>CO$_2$ emission from the running of backup battery</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Electric Power Company</th>
<th>Power generation cost by backup battery</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>System stabilization costs</td>
</tr>
<tr>
<td></td>
<td>Avoidable cost</td>
</tr>
</tbody>
</table>

3.3.1 Design Variables

Design variables are necessary for solving optimization problem. Design variables used in this section and next section are showed in Table 3.2. Variables $x_{1t} \sim x_{5t}$ describe the amount of electric power [Wh] flowing among objects in Figure 3.?, whose meanings are shown in Table 3.2 respectively. Subscript $t$ means time. In this research, in order to realize the optimal amount of electric power flowing among objects every hour within 24-hour one day, $t$ takes the value from 1 to 24. $x_6$ represents battery capacity [kWh]. If battery is not introduces into house, $x_6$ takes the value of 0.

Table 3.2 Design Variables

<table>
<thead>
<tr>
<th>Design Variables</th>
<th>$x_{1t}$</th>
<th>$x_{2t}$</th>
<th>$x_{3t}$</th>
<th>$x_{4t}$</th>
<th>$x_{5t}$</th>
<th>$x_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meaning</td>
<td>$PV2G_t$</td>
<td>$G2H_t$</td>
<td>$G2B_t$</td>
<td>$PV2B_t$</td>
<td>$B2H_t$</td>
<td>Battery Capacity</td>
</tr>
</tbody>
</table>
3.3.2 Integrated Objective Function

Objective Function in this research is the integration of every stakeholder cost, which is written as Formula (1). CostH means household cost. CostG means government cost. CostE means electric power company cost. \( \alpha, \beta \) are weight coefficients which can be changeable depending on the contribution of every stakeholder. \( \alpha, \beta \) are both more than 0 and less than 1.

In this research, the optimization problem is to find the best solution for minimizing objective function. Mixed-integer linear programming is used as method, which was described in Section 3.2.

Set \( \text{Cost}(x) \) be the total cost of one day.

\[
\text{Minimize Cost} \\
\text{Cost}(x) = \alpha \cdot \text{CostH}(x) + \beta \cdot \text{CostG}(x) + (1 - \alpha - \beta) \cdot \text{CostE}(x) \quad (1) \\
x = (x_{1t}, x_{2t}, ..., x_{5t}, x_6) \\
such that \\
0 \leq \alpha, \beta, 1 - \alpha - \beta \leq 1
\]

3.3.3 Household Cost

Formula (2) is the formalization of household cost (\( \text{CostH} \) in Formula (1)) based on Table 3.1. On the right side of Formula (2), summation of electric power purchase cost from electric power company and profits from the selling of surplus electric power per hour are calculated with sigma. The rest parts are installation cost of battery and PV, and subsidy of battery and PV from government.

The installation cost and subsidy of battery and PV in this formula are values per day considering the number of years in use. The specific value of each symbol will be explained in next chapter.

\[
\text{CostH}(x) = \sum_{t=1}^{24} \{EC_t \cdot (x_{2t} + x_{3t}) - FIT \cdot x_{1t}\} + \text{BUP} \cdot x_6 + \text{CPV} \\
- \text{SPV} - \text{SB} \quad (2)
\]
All symbols are explained as follows.

\( \text{Cost}_H \): objective function of household cost
\( EC_t \): electric power rate at time \( t \) [Yen/Wh]
\( FIT \): feed-in tariff, price of selling surplus electric power [Yen/Wh]
\( BUP \): introduction cost of battery [Yen/kWh]
\( CPV \): introduction cost of PV [Yen]
\( SPV \): subsidy of PV [Yen]
\( SB \): subsidy of battery [Yen]

### 3.3.4 Government Cost

Formula (3) is the formularization of government cost (\( \text{Cost}_G \) in Formula (1)). In this research, government cost is acquired by converting the amount of CO\(_2\) emission into the value of currency. On the right side of Formula (3), it shows life cycle CO\(_2\) emissions from electric power company and from power generation by PV. Life cycle CO\(_2\) emissions mean CO\(_2\) emission from electric power generation, the construction phase of plants and equipment, and mining, transportation of raw materials and fuels, etc.

Formula (4) shows how to calculate life cycle CO\(_2\) emissions from the purchase and selling of electric power between electric power company and household, which include CO\(_2\) emission from power generation and the running of backup battery that deals with surplus electric power.

Carbon Tax used in this research is introduced in Chapter 5. For backup battery which deals with surplus power, it is assumed to be petroleum power, which is easy to deal with output fluctuation [33].

\[
\text{Cost}_G(x) = \text{Tax} \cdot \{ETCO2 + PVCO2 \cdot PVSUM\}
\]

\[
ETCO2 = \sum_{t=1}^{24} \{ESCO2 \cdot (x_{2t} + x_{3t}) + BUCO2 \cdot x_{1t}\}
\]

All symbols are explained as follows.

\( \text{Cost}_G \): objective function of government cost
Tax: carbon tax [Yen/t-CO2]
ETCO2: life cycle CO2 emissions from the purchase and selling of electric power [t-CO2]
PVC02: life cycle CO2 emissions from power generation by PV [t-CO2/Wh]
PVSUM: total electric power generated by PV [Wh]
ESCO2: life cycle CO2 emissions from power generation by electric power company [t-CO2/Wh]
BUICO2: life cycle CO2 emissions from the running of backup battery [t-CO2/Wh]

3.3.5 Electric Power Company Cost

Formula (5) is the formularization of electric power company cost (CostE in Formula (1)). With Formula (5), electric power company cost includes system stabilization cost dealing with the selling of surplus electric power by household and avoidable cost.

\[
CostE(x) = \sum_{t=1}^{24} \{CBU + CEG - AVO \} \cdot x_{1t}
\]  

(5)

All symbols are explained as follows.

CostE: objective function of electric power company cost
CBU: running cost of backup battery [Yen/Wh]
CEG : system stabilization cost dealing with the selling of surplus electric power [Yen/Wh]
AVO : avoidable cost [Yen]. When electric power company purchases surplus power generated by renewable energy like solar power, the company can avoid the cost of generating that amount of electric power [33].
3.4 Constraints

The following Formula (6) ~ Formula (14) are constraints. In this research, since the amount of electric power flowing among elements in Figure 3.2 is changing from hour to hour, constraints are for the consistency of amount of electric power per hour. Following is explanations of each formula.

Formula (6) shows the balance of PV output. Household has priority to consume the electric power generated by PV ($PV2H_t$). If surplus power occurs, it is either sold to electric power company ($x_i$) or stored in battery ($x_{st}$). In this case, the constraint makes certain that the amount of electric power generated by PV ($PV_t$) equals to the sum of amount used by household, sold to electric power company and stored in battery.

Formula (7) shows the balance of household’s electric power demand. Electric power generated by PV is firstly used by household. If that amount is not enough for household demand, the purchase of electric power from electric power company ($x_{A}$) or/and the discharge of battery ($x_{L}$) happen in order to fulfill the demand. In this case, the constraint assures that the amount of household’s electric power demand ($Dem_t$) is the same as the total amount of electric power got from PV, bought from electric power company and got from battery.

Formula (8) shows the amount of electric power consumed by household, which is generated by PV. If the amount of electric power generated by PV ($PV_t$) at time $t$ is less than household’s electric power demand ($Dem_t$) at that time, the amount of PV generated electric power used by household ($PV2H_t$) equals to the amount of power generated by PV. On the contrary, it equals to household’s electric power demand.

Formula (9) shows charge and discharge state of battery. The amount of electric power stored in battery ($SOCB_t$) at time $t$ is calculated by firstly summing up the amount of electric power that is stored in battery one hour ago ($SOCB_{t-1}$), purchased from electric power company ($x_{3t}$), and surplus power stored in battery ($x_{st}$), and then subtracting the amount of electric power discharged from battery ($x_{st}$) from it. During charging and discharging phases, transition loss happens. Therefore, coefficient of charge/discharge efficiency ($\omega$) is used.

Formula (10) shows the constraint on amount of charging and discharging power of battery per hour due to power conditioner. The right side of Formula (10) shows the maximum amount of possibly charge/discharge electric power per hour. The left side means that the sum of the amount of electric power stored in battery which is purchased
from electric power company \((x_{3t})\), the amount of surplus power stored in battery \((x_{4t})\), and the amount of electric power discharged from battery \((x_{5t})\) equals to the maximum amount of possibly charge/discharge electric power per hour.

Formula (11) shows the possible amount of power that battery can provide house with. It means that the amount of electric power discharged from battery \((x_{5t})\) during every hour is less than the total amount of electric power stored in battery at that time \((SOCB_t)\).

Formula (12) shows the minimum and maximum charged capacity of battery. In this research, the minimum charged capacity of battery is assumed as 15% of total battery capacity and the maximum is 85% in consideration of safety.

Formula (13) shows default setting of battery’s charged capacity. In other words, it shows the remaining amount of electric power stored in battery the day before. In this research, default setting of battery’s charged capacity is set as the minimum charged capacity of battery.

Formula (14) means all the designed variables are nonnegative. Under this setting, it ensures that the electric power flowing among elements in Figure 3.2 dose not flow in opposite way.

for \(\forall_t \in [1,24]\)

\[
P_{V_t} = P_{V2H_t} + x_{1t} + x_{4t} \quad (6)
\]

\[
Dem_t = P_{V2H_t} + x_{2t} + x_{5t} \quad (7)
\]

\[
\begin{cases}
P_{V2H_t} = P_{V_t} & (P_{V_t} < Dem_t) \\
P_{V2H_t} = Dem_t & (P_{V_t} \geq Dem_t)
\end{cases} \quad (8)
\]

\[
SOCB_t = SOCB_{t-1} + \omega \cdot (x_{3t} + x_{4t}) - \frac{1}{\omega} \cdot x_{5t} \quad (9)
\]

\[
x_{3t} + x_{4t} + x_{5t} \leq x_6 \cdot PCSB \cdot R \quad (10)
\]

\[
x_{5t} \leq SOCB_t \quad (11)
\]

\[
SOCB_{min} \leq SOCB_t \leq SOCB_{max} \quad (12)
\]
\[ SOCB_0 = SOCB_{\min} \] (13)

\[ 0 \leq x_{1t}, x_{2t}, x_{3t}, x_{4t}, x_{5t}, x_{6} \] (14)

All symbols are explained as follows.

\( PV_t \): the amount of electric power generated by PV at time \( t \) [Wh]

\( PV2H_t \): the amount of electric power generated by PV that is used by household at time \( t \) [Wh]

\( Dem_t \): household electric power demand at time \( t \) [Wh]

\( SOCB_t \): charge state of battery at time \( t \) [Wh]

\( \omega \): charge/discharge efficiency [%]

\( PCSB \): battery’s instantaneous output per battery capacity [kW/kWh]

\( R \): change coefficient (kW → Wh)

\( SOCB_{\min} \): minimum charge capacity of battery [Wh]

\( SOCB_{\max} \): maximum charge capacity of battery [Wh]

### 3.5 Verification of the Model

This section describes how to verify whether the built model outputs the result correctly. Since the optimization calculation by mixed-integer linear programming (MILP) of MATLAB has been verified by The MathWorks, Inc., the verification here means whether the inputs to the model are processed correctly to get the feasible solutions. The verification is implemented by inputting extreme values or extreme situations into the model and checking whether the assumed results are outputted [22] [34].

The five specific verifications are described as follows.

- When no electric power is generated by PV (\( PV_t = 0 \)), whether the electric power consumed by households is only purchased from electric power companies (whether only \( x_{2t} \neq 0 \))
• When no electric power is needed by households (\(Dem_t = 0\)), whether the households purchase electric power from electric power companies (whether \(x_{2t} \neq 0\))

• When the battery price is extremely high (for example, 1000 times higher than usual), whether the introduction of the battery system is implemented (whether \(x_{6t} = 0\))

• When the possible charging/discharging amount of electric power of the battery system is 0 (\(PCS_B = 0\)), whether the surplus power generated by PV and the electric power purchased from the electric power company are stored (whether \(x_{4t} = 0, \ x_{3t} = 0\)), and whether the battery system conducts discharging (whether \(x_{5t} = 0\))

• When the amount of surplus power that can be sold to the electric power company is limited as 0 (set \(x_{1t} = 0\) on purpose), and the possible charging/discharging amount of electric power of the battery system is 0 (\(PCS_B = 0\)), whether the feasible solution can be found or not

By testing the above conditions, all the assumed results were achieved. Therefore, it verified the model that is built in this research outputs results correctly.
4. Preconditions

4.1 Household Electric Power Consumption

In this research, target household is average existing house in each region. As inputs to the model described in Chapter 3, average amount of electric power demand of a house is considered. Furthermore, since the amount of electric power demand per hour in one day is used in the model, it is necessary to search for average amount of electric power demand per hour in every region. However, there is no reference including that data can be found. In this research, regional average amount of electric power demand per hour ($Dem_t$ in Formula (7) and Formula (8)) is calculated based on open data. The procedure for calculation is shown in Figure 4.1. According to the procedure, firstly, the amount of electric power consumption of a house per day in each region is calculated, the details of which are explained in next paragraph. Then with the calculation results of regional average amount of electric power consumption of a house per day and the data of regional electric power consumption ratio of domestic appliances, regional average amount of electric power consumption of every domestic application in a house per day is calculated. Finally, with another data of electric power consumption ratio of every domestic application in one hour, household electric power consumption per hour in every region is calculated.
Figure 4.1 Procedure for Calculating Electric Power Consumption

Since the data of regional average amount of electric power consumption of a house per day ($ECHR_i$) cannot be found in any open resources, in this research, it is calculated by Formula (17), which is based on Formula (15) and Formula (16). In Formula (15), the left side means that in region $i$, the sum of electric power consumption of houses ($RatioH \cdot ECHR_i$) and of apartments ($RatioA \cdot ECAR_i$) equals to the amount of household electric power consumption ($ECR_i$), which is shown in the right side. In Formula (16), it assumes that the ratio of electric power consumption of a house to electric power consumption of an apartment in region $i$ ($ECHR_i/ECAR_i$) is the same as that in the whole Japan ($ECH/ECAR$). Based on Formula (15) and Formula (16), average amount of electric power consumption of a house per day in every region ($ECHR_i$) can be calculated by Formula (17).
\[ \text{Ratio}_H \cdot ECHR_i + \text{Ratio}_A \cdot ECAR_i = ECR_i \quad (15) \]

\[ ECHR_i / ECAR_i = ECH / ECA \quad (16) \]

\[ i = 1(\text{Kyushu}), 2(\text{Kansai}), 3(\text{Kanto}), 4(\text{Tohoku}), 5(\text{Hokkaido}) \]

\[ ECHR_i = ECR_i / (\text{Ratio}_H + \text{Ratio}_A \cdot ECAR_i / ECH) \quad (17) \]

All symbols are explained as follows.

\text{Ratio}_H: \text{the ratio of houses to all kinds of residences [\%]}
\text{Ratio}_A: \text{the ratio of apartments to all kinds of residences [\%]}
i: \text{regions [Kyushu, Kansai, Kanto, Tokyo, Hokkaido]}
ECHR_i: \text{daily average amount of electric power consumption of a house in region } i \text{ [kWh/household\text{-}day]}
ECAR_i: \text{daily average amount of electric power consumption of an apartment in region } i \text{ [kWh/household\text{-}day]}
ECR_i: \text{daily average amount of household electric power consumption in region } i \text{ [kWh/household\text{-}day]}
ECH: \text{daily average amount of electric power consumption of a house in Japan [kWh/household\text{-}day]}
ECA: \text{daily average amount of electric power consumption of an apartment in Japan [kWh/household\text{-}day]}

Region 1~5 represent Kyushu, Kansai, Kanto, Tohoku and Hokkaido respectively. Daily average amount of household electric power consumption in region \( i \) (ECR_i in Formula (17)) is shown in Table 4.1 based on reference [35]. According to reference [36], the ratio of houses to all types of residence (Ratio\(_H \) in Formula (17)) is 51.1\%, and the ratio of apartments to all types of residence (Ratio\(_A \) in Formula (17)) is 48.9\%. Daily average amount of electric power consumption of a house and of an apartment in the whole Japan are listed in Table 4.2 based on reference [35]. Above all of these data, calculation results of daily average amount of electric power consumption of a house in region \( i \) (ECHR_i in Formula (17)) are shown in Table 4.3.
Table 4.1 Regional Household Electric Power Consumption
(Made by Author Based on Reference [35])

<table>
<thead>
<tr>
<th>Region</th>
<th>Household Electric Power Consumption [kWh/household·day]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kyushu</td>
<td>15.274</td>
</tr>
<tr>
<td>Kansai</td>
<td>13.400</td>
</tr>
<tr>
<td>Kanto</td>
<td>12.619</td>
</tr>
<tr>
<td>Tohoku</td>
<td>18.904</td>
</tr>
<tr>
<td>Hokkaido</td>
<td>11.647</td>
</tr>
</tbody>
</table>

Table 4.2 Electric Power Consumption of a House/Apartment in Japan
(Made by Author Based on Reference [35])

<table>
<thead>
<tr>
<th>Number of Households</th>
<th>Electric Power Consumption of a House [kWh/household·day]</th>
<th>Electric Power Consumption of an Apartment [kWh/household·day]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.063</td>
<td>6.488</td>
</tr>
<tr>
<td>2</td>
<td>14.693</td>
<td>9.655</td>
</tr>
<tr>
<td>3</td>
<td>18.041</td>
<td>11.200</td>
</tr>
<tr>
<td>4</td>
<td>20.378</td>
<td>12.052</td>
</tr>
<tr>
<td>5</td>
<td>23.422</td>
<td>12.844</td>
</tr>
<tr>
<td>6 ~</td>
<td>26.490</td>
<td>13.364</td>
</tr>
<tr>
<td>Average</td>
<td>18.682</td>
<td>10.934</td>
</tr>
</tbody>
</table>

Table 4.3 Regional Electric Power Consumption of a House

<table>
<thead>
<tr>
<th>Region</th>
<th>Electric Power Consumption of a House [kWh/household·day]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kyushu</td>
<td>19.159</td>
</tr>
<tr>
<td>Kansai</td>
<td>16.808</td>
</tr>
<tr>
<td>Kanto</td>
<td>15.830</td>
</tr>
<tr>
<td>Tohoku</td>
<td>23.712</td>
</tr>
<tr>
<td>Hokkaido</td>
<td>14.608</td>
</tr>
</tbody>
</table>
Electric power consumed by household is for a variety of uses, and consuming time slot differs depending on the kind of uses. For example, when electric power is used for hot water supply, the amount of electric power consumption increases during the night. Therefore, in this research, regional average amount of electric power consumption of a house per day calculated before is decomposed by different kinds of applications. At this moment, the applications of electric power consumption are assumed as application for heating, cooling, hot water and others like kitchen, lighting, etc. Electric power consumption ratios of domestic appliances in every region are shown in Table 4.4 based on reference [35]. In reference [35], energy consumption for heating, cooling, hot water, kitchen, lighting and others are categorized by different energy sources like electric power, city gas, LP gas, kerosene and solar hear. In this research, only electric power is considered. Others in Table 4.4 include uses for kitchen, lighting and others of reference [35]. About regions, Kyushu belongs to South Japan, Kansai and Kanto belong to Middle Japan, and Tohoku and Hokkaido belong to North Japan.

Table 4.4 Electric Power Consumption Ratios of Different Applications
(Made by Author Based on Reference [35])

<table>
<thead>
<tr>
<th>Region</th>
<th>Heating (%)</th>
<th>Cooling (%)</th>
<th>Hot Water (%)</th>
<th>Others (%)</th>
<th>Total (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Japan</td>
<td>12.42</td>
<td>3.73</td>
<td>26.70</td>
<td>57.15</td>
<td>100</td>
</tr>
<tr>
<td>Middle Japan</td>
<td>14.39</td>
<td>4.29</td>
<td>15.01</td>
<td>66.31</td>
<td>100</td>
</tr>
<tr>
<td>North Japan</td>
<td>17.24</td>
<td>2.13</td>
<td>28.22</td>
<td>52.41</td>
<td>100</td>
</tr>
</tbody>
</table>

With average amount of electric power consumption of a house per day (shown in Table 4.3) and electric power consumption ratios of different domestic appliances (shown in Table 4.4) in every region, regional average amount of electric power consumption by application in a house per day is calculated shown in Table 4.5.
Table 4.5 Regional Electric Power Consumption for Different Applications in a House

<table>
<thead>
<tr>
<th>Region</th>
<th>Heating [kWh/household-day]</th>
<th>Cooling [kWh/household-day]</th>
<th>Hot Water [kWh/household-day]</th>
<th>Others [kWh/household-day]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kyushu</td>
<td>2.380</td>
<td>0.715</td>
<td>5.115</td>
<td>30.108</td>
</tr>
<tr>
<td>Kansai</td>
<td>2.419</td>
<td>0.721</td>
<td>2.523</td>
<td>11.145</td>
</tr>
<tr>
<td>Kanto</td>
<td>2.278</td>
<td>0.679</td>
<td>2.376</td>
<td>10.497</td>
</tr>
<tr>
<td>Tohoku</td>
<td>4.088</td>
<td>0.505</td>
<td>6.692</td>
<td>13.551</td>
</tr>
<tr>
<td>Hokkaido</td>
<td>2.518</td>
<td>0.311</td>
<td>4.122</td>
<td>8.348</td>
</tr>
</tbody>
</table>

Then, for the purpose of calculating amount of electric power consumption by application in a house per hour, electric power consumption ratio of domestic appliances in one hour is needed, which is included in reference [37]. The applications of electric power consumption in reference [37] are divided into application for heating, cooling, hot water and others as well. However, ratios of different applications are shown in three seasons respectively, which are summer, winter and interim season. In this research, consumption ratio of application for heating refers to values in winter, consumption ratio of application for cooling refers to values in summer, and consumption ratios of application for hot water and others refer to values in interim season both. Based on reference [37], consumption ratios of domestic appliances per hour assumed in this research is shown in Figure 4.2.
Finally, regional amount of electric power consumption of a house per hour is calculated by the following two steps. Firstly, amount of electric power consumption for heating, cooling, hot water and others are calculated respectively based on the data in Table 4.5 and Figure 4.2. Then, by summing electric power consumption for heating, cooling, hot water and others up in every hour, amount of electric power consumption of a house at that time is calculated, which is shown in Figure 4.3.
4.2 Electric Power Generated by Photovoltaic

Electric power generated by PV (\(PV_t\) in Formula (6) and Formula (8)) is calculated by Formula (18). Formula (18) is based on reference [38]. From the right side of Formula (18), the amount of solar irradiance per square meter is necessary for calculating the amount of electric power generated by PV. For the data of the amount of solar irradiance, database METPV-11 (Meteorological Test Data for Photovoltaic System) from New Energy and Industrial Technology Development Organization (NEDO) [39] is used in this research. In METPV-11, the amount of solar irradiance in every hour and in every city is collected. In this research, since Kyushu region, Kansai Region, Kanto Region, Tohoku Region and Hokkaido Region 5 regions are considered, the data in Fukuoka City, City of Osaka, Tokyo City, City of Sendai and City of Sapporo represent each region respectively. Furthermore, the annual average of solar irradiance is used. The details of solar irradiance data attributes are listed in Table 4.6. According to Formula (18), power generation efficiency and panel area of PV are needed as well. Especially for power generation efficiency, it is difficult to decide what date to use, because of the large variety of open data. In this research, power generation efficiency and panel area are set according to the product sold in real market. The data of SPR-X21-
345 from Toshiba [40] is used in this research because of high power generation efficiency as household PV. In addition, according to reference [41], one Japanese household’s electric power consumption per year is around 4,734 kWh, which can be produced by PV system with 4kW capacity. Therefore, in this research, capacity of PV system takes the value of 4 kW. On the basis of the above consideration, calculated power generation by PV in all 5 regions are shown in Figure 4.4 ~ Figure 4.8. From these figures, it can be seen that the amount of electric power generated by PV is high during day time when solar irradiance is affluent.

\[
PV_t = INS_t \cdot PVEFF \cdot PVUA \cdot PVVOL
\]  

(18)

All symbols are explained as follows.

\( PV_t \): the amount of electric power generated by PV [Wh]

\( INS_t \): solar irradiance per square meter at time t [Wh/m²]

\( PVEFF \): power generation efficiency of PV [%]

\( PVUA \): PV panel area for generating 1kW electric power [m²/kW]

\( PVVOL \): capacity of PV system [kW]

Table 4.6 Solar Irradiance Data Attributes

<table>
<thead>
<tr>
<th>City</th>
<th>Optimal Angle of Inclination of the Year [42]</th>
<th>Azimuth</th>
<th>Year Information</th>
<th>INS(_t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fukuoka</td>
<td>26.1°</td>
<td></td>
<td>1990 ~ 2009</td>
<td>Average Value of the Whole Year</td>
</tr>
<tr>
<td>Osaka</td>
<td>29.2°</td>
<td>Due South</td>
<td>Average Sunlight Year</td>
<td></td>
</tr>
<tr>
<td>Tokyo</td>
<td>32.8°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sendai</td>
<td>34.5°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sapporo</td>
<td>34.8°</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 4.4 Electric Power Generated by PV (Kyushu)

Figure 4.5 Electric Power Generated by PV (Kansai)
Figure 4.6 Electric Power Generated by PV (Kanto)

Figure 4.7 Electric Power Generated by PV (Tohoku)
Furthermore, it is reported that efficiency of PV is increasing due to technology development and there are goals for it in Japan [24] [43]. In these two references, PV technology road maps in 2020 and 2030 are described. However, power generation efficiency of PV differs from panel material and the prediction of future PV efficiency is full of uncertainty. In this research, technology development is assumed as high, standard and low development cases, which are shown in Table 4.7.

<table>
<thead>
<tr>
<th>Table 4.7 Future Efficiency PVEFF of PV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>High Technology Case [%]</td>
</tr>
<tr>
<td>Standard Technology Case [%]</td>
</tr>
<tr>
<td>Low Technology Case [%]</td>
</tr>
</tbody>
</table>

### 4.3 Electric Power Rate

While purchasing electric power from electric power company, electric power rate ($EC_r$ in Formula (2)) is referred to rate system of electric power company in every region. For Kyushu region, rate system of Kyushu Electric Power Company is used [44]. For Kansai region, rate system of Kansai Electric Power company is used [45]. For Kanto
region, rate system of Tokyo Electric Power Company Holdings is used [46]. For Tohoku region, rate system of Tohoku Electric Power Company is used [47]. For Hokkaido region, rate system of Hokkaido Electric Power Company is used [48]. To be specific about the rate systems used in this research, for all regions, they are based on night advantage plans of electric power companies as shown in Table 4. For example, in Kanto region, electric power rate is 32.14 Yen/kWh from 7 am to 11 pm, and it is 20.78 Yen/kWh from 11pm to 7am of next day.

Table 4.8 Electric Power Rate

<table>
<thead>
<tr>
<th>Region</th>
<th>Electric Power Rate [Yen/kWh]</th>
<th>7am~11pm</th>
<th>11pm~7am (next day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kyushu</td>
<td>0~90 kWh</td>
<td>20.87</td>
<td></td>
</tr>
<tr>
<td></td>
<td>90~230 kWh</td>
<td>27.56</td>
<td>14.13</td>
</tr>
<tr>
<td></td>
<td>230kWh~</td>
<td>31.13</td>
<td></td>
</tr>
<tr>
<td>Kansai</td>
<td>0~90 kWh</td>
<td>21.64</td>
<td></td>
</tr>
<tr>
<td></td>
<td>90~230 kWh</td>
<td>28.59</td>
<td>10.92</td>
</tr>
<tr>
<td></td>
<td>230kWh~</td>
<td>32.76</td>
<td></td>
</tr>
<tr>
<td>Tokyo</td>
<td></td>
<td>32.14</td>
<td>20.78</td>
</tr>
<tr>
<td>Tohoku</td>
<td>0~90 kWh</td>
<td>21.69</td>
<td></td>
</tr>
<tr>
<td></td>
<td>90~230 kWh</td>
<td>29.58</td>
<td>9.94</td>
</tr>
<tr>
<td></td>
<td>230kWh~</td>
<td>34.19</td>
<td></td>
</tr>
<tr>
<td>Hokkaido</td>
<td>0~90 kWh</td>
<td>28.08</td>
<td></td>
</tr>
<tr>
<td></td>
<td>90~210 kWh</td>
<td>35.66</td>
<td>10.02</td>
</tr>
<tr>
<td></td>
<td>210kWh~</td>
<td>40.10</td>
<td></td>
</tr>
</tbody>
</table>

### 4.4 Feed-in Tariff

In this research, Feed-in Tariff (FIT in Formula (2)) takes the value of 30 Yen/kWh in the year 2017 according to FIT policy [23]. However, since FIT price has been updating every year, the price of FIT changes due to the year of PV introduction. And new policy has been put into action since 2017. Figure 4.9 shows FIT changes since FIT policy was firstly taken into effect in 2012. It can be seen that FIT was 42 Yen/kWh at the beginning of FIT policy, and it becomes 30 Yen/kWh in 2017. It is predicted to be
28 Yen/kWh in 2018 and 2019 Yen/kWh. Yearly 2 Yen/kWh decrease is expected under new policy.

Figure 4.9 Changes of FIT

As FIT decreases along with the decline of PV power generation cost [49], the future price of FIT is assumed as shown in Table 4.9, which is classified into three cases as high, standard and low technology cases. In high technology case, FIT in 2030 aims at 0 Yen. In standard technology case, it is assumed that FIT decreases 2 Yen/kWh per year according to new policy. In low technology case, FIT aims at 7 Yen according to reference [49].

<table>
<thead>
<tr>
<th>Year</th>
<th>2017</th>
<th>2025</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Technology Case [Yen/kWh]</td>
<td>30</td>
<td>11.5</td>
<td>0</td>
</tr>
<tr>
<td>Standard Technology Case [Yen/kWh]</td>
<td>30</td>
<td>14</td>
<td>4</td>
</tr>
<tr>
<td>Low Technology Case [Yen/kWh]</td>
<td>30</td>
<td>15.85</td>
<td>7</td>
</tr>
</tbody>
</table>
4.5 Introduction Price of Photovoltaic

Present and future introduction price of PV are shown in Table 4.10. Residential PV system price ($CPV$ in Formula (2)) for existing houses refers to reference [50]. The introduction price listed in Table 4.10 includes construction costs of PV and the cost of power conditioner, which transfers direct current (DC) generated by PV to alternating current (AC) that is able to be used in a house.

In this research, since cost per day is considered, $CPV$ in Formula (2) is calculated by dividing the price in Table 4.10 by the number of years in use and 365 days. Although the legal running year of PV is 17 years [51], considering the purchasing span of FIT which is 10 years, the number of years in use takes the value of 10 in this research.

<table>
<thead>
<tr>
<th>Year</th>
<th>2017</th>
<th>2025</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price [Yen/kW]</td>
<td>371,000</td>
<td>171,000</td>
<td>121,000</td>
</tr>
</tbody>
</table>

Table 4.10 Introduction Price of PV System

Figure 4.10 shows the changes of PV introduction price for existing houses. According to reference [50], residential PV system price for existing houses in 2017 is 371,000 Yen/kW. From Figure 4.10, it can be seen that introduction price of PV has been decreasing in recent years, which is related to the diffusion of PV system and FIT, and decreasing price of PV accessories made in China. In this research, it is assumed that PV cost decreases 25,000 Yen/kW per year from 2017 to 2015. Therefore, in 2025, the introduction price of PV is 171,000 Yen/kW. Furthermore, considering that the rate of cost decrease will slow down, it is predicted that PV cost decreases 10,000 Yen/kW per year from 2025 to 2030. Thus, the introduction price of PV in 2030 is 121,000 Yen/kW.
4.6 Introduction Price of Battery

Introduction price of battery ($C_B$ in Formula (2)) is shown in Table 4.11. Figure 4.11 shows introduction prices of 10-year-life and 11-year-life batteries based on reference [52]. Here, the price in 2016 reflects real market, and prices after 2017 are goals. It can be seen that in the same year, the price of 11-year-life battery is higher than 10-year-life battery, but the prices per year are same. For example, in the year of 2017, introduction prices of 10-year-life and 11-year-life batteries are both 15,000 Yen/kW per year. Therefore, in this research, introduction prices of 10-year-life battery are considered. About the prediction of battery prices in 2025 and in 2030, if the tendency in Figure 4.11 is considered, with 30,000 Yen/kWh decrease per year, battery price will be 0 in 2022, which is impossible. Therefore, in this research, it is assumed that price in 2025 is 30,000 Yen/kWh and 15,000 Yen/kWh in 2030.

Moreover, since cost per day is taken into consideration in this research, $C_B$ in Formula (2) is calculated by dividing prices in Table 4.11 by 10 years and 365 days.
Table 4.11 Introduction Price of Battery

<table>
<thead>
<tr>
<th>Year</th>
<th>2017</th>
<th>2025</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction Price of Battery [Yen/kWh]</td>
<td>150,000</td>
<td>30,000</td>
<td>15,000</td>
</tr>
</tbody>
</table>

Figure 4.11 Introduction Price of 10-year-life and 11-year-life Battery
(Made by Author Based on Reference [52])

4.7 Subsidy of Photovoltaic and Battery

Subsidy of PV and Battery (SPV and SB in Formula (2)) in 2017 of every region is shown in Table 4.12. For Kyushu region, subsidy in Fukuoka is used [53]. For Kansai region, subsidy in East Osaka City is used [54]. For Kanto region, subsidy in Chiyoda-ku is used [55]. For Tohoku region, subsidy in Miyagi prefecture is used [56]. For Hokkaido region, subsidy in Sapporo is used [57].

Since subsidy in all regions is decreasing year by year, in this research, it is predicted that subsidy in 2025 is half of present price, and subsidy in 2030 is 0 for both PV and battery.
4.8 Parameters of Battery

Battery capacity ($x_e$ in Table 3.2) is calculated by solving optimization problem. Battery’s maximum charging and discharging capacity per hour ($PCS_B$ in Formula 10) is referred to battery sold in real market [58], whose possible charging capacity is 8.4kWh and maximum output is 2kW. For that battery, capacity is 2kW/4.8kWh. And maximum charge/discharge capacity is calculated by multiplying battery capacity by 1 hour.

Charge/discharge efficiency of battery ($\omega$ in Formula 9) is assumed as 85% in this research according to reference [59]. However, considering technology development, efficiency is predicted as 95% in 2025, and 99% in 2030.

4.9 CO₂ Emission Intensity

The data of CO₂ emission factor (ESCO2 in Formula 4) in each region in 2017 are available in the website of each electric power company [60] [61] [62] [63] [64]. CO₂ emission factors are listed in Table 4.13.
### Table 4.13 CO₂ Emission Factor

<table>
<thead>
<tr>
<th>Region</th>
<th>CO₂ Emission Factor [kg-CO₂/kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kyushu</td>
<td>0.463</td>
</tr>
<tr>
<td>Kansai</td>
<td>0.418</td>
</tr>
<tr>
<td>Kanto</td>
<td>0.463</td>
</tr>
<tr>
<td>Tohoku</td>
<td>0.523</td>
</tr>
<tr>
<td>Hokkaido</td>
<td>0.678</td>
</tr>
</tbody>
</table>

### 4.10 Future Composition Ratio of Power Supply

Composition ratio of power supply has drastic effect on CO₂ emission factor. When it comes to future CO₂ emission factor ($ESCO_2$ in Formula (4)), it is calculated by Formula (19) regardless of region differences in this research. Composition ratios of power supply in 2017 and 2030 are shown in Table 4.14 based on reference [65] [66]. Composition ratio in 2025 takes the average of 2017 and 2030.

$$ESCO_2 = \sum_{i=1}^{5} EM_i \cdot EL_i$$  \hspace{1cm} (19)

\[
i = 1(Coal), 2(LNG), 3(Petroleum), 4(Renewable\ Energy), 5(Nuclear)
\]

All symbols are explained as follows.

- $EM_i$: Composition ratio of power supply $i$ [%]
- $EL_i$: CO₂ emission from power supply $i$ life cycles [t-CO₂/Wh]

### Table 4.14 Composition Ratio of Power Supply [%]

<table>
<thead>
<tr>
<th>Year</th>
<th>Coal</th>
<th>LNG</th>
<th>Petroleum</th>
<th>Renewable Energy</th>
<th>Nuclear</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>32.6</td>
<td>43.2</td>
<td>3.7</td>
<td>13.1</td>
<td>3.4</td>
</tr>
<tr>
<td>2025</td>
<td>29.3</td>
<td>25.1</td>
<td>3.35</td>
<td>18.55</td>
<td>11.7</td>
</tr>
<tr>
<td>2030</td>
<td>26</td>
<td>27</td>
<td>3</td>
<td>24</td>
<td>20</td>
</tr>
</tbody>
</table>
4.11 CO₂ Emission Intensity

Lifecycle CO₂ emission intensities of PV and other power supplies in Table 10 (\(P_{VC\text{T}O}\) in Formula (3) and \(E_L\) in Formula (19)) are assumed according to reference [67] as shown in Figure 4.12. CO₂ emission factor of renewable energy takes the average of power generation by wind power, solar power, hydropower and geothermal power shown in Figure 4.12. Furthermore, in Figure 4.12, fuel combustion for power generation (direct) in orange color means CO₂ emission from the burning of fuels, and others (indirect) in blue color means CO₂ emission from the construction and running of power generation facility.

![Figure 4.12 LC-CO₂ Emission from Each Power Supply](image)

(Made by Author Based on Reference [67])

4.12 System Stabilization Costs

It is assumed that system stabilization costs (\(CEG\) in Formula (5)) are 0.8 Yen/kWh, 4 Yen/kWh and 8 Yen/kWh while the amount of electric power generated by photovoltaic accounts for 0~2%, 2~5% and 5~10% of total power generation respectively according to reference [68]. For each region, the amount of electric power generated by photovoltaic is 2.9% of total power generation in Hokkaido region, 2.4% in Tohoku
region, 1.2% in Kanto region, 1.5% in Kansai region and 2.5% in Kyushu region from reference [69]. Therefore, system stabilization costs are 4 Yen/kWh in Hokkaido, Tohoku and Kyushu regions, and 0.8 Yen/kWh in Kanto and Kansai regions.

It is predicted that system stabilization costs will increase to 10 Yen/kWh in 2030 because of the increase in the amount of electric power generated by PV, and additional costs to substitute wind and solar power for nuclear power according to reference [70]. Therefore, in this research, system stabilization costs are assumed as 8 Yen/kWh in 2025, and 10 Yen/kWh in 2030 for all regions.

4.13 Other Preconditions

Power generation cost of backup battery (\( CBU \) in Formula (5)) is referred to power generation cost of petroleum from reference [33], which is 22.1 Yen/kWh.

Avoidable cost (\( AVO \) in Formula (5)) is set by data of September 2018 from reference [71].
5. Carbon Tax Design

In Japan, there is *tax for global warming countermeasure* in regard to CO₂ emission from household. It aims to control CO₂ emission from the usage of energy [72]. However, in order to make maximum control of CO₂ emission from the usage of energy, it is necessary for household to make full use of electric power generated by PV. With current tax policy, it is economically rational for household to sell surplus power generated by PV and purchase electric power that is insufficiently generated by PV from electric power company. Therefore, carbon tax taken in this research is for the purpose of promoting efficient use of electric power generated by PV.

In this research, carbon tax design is based on previous study [22].

5.1 Taxable Objectives and Scope

In this design of carbon tax, taxable objects are electric power consumed by household, which is purchased from electric power company and generated by PV. Evaluation Scope includes life cycle CO₂ emission from production and consumption of 1kWh electric power in household, and economic cost along with electric power consumption. As life cycle CO₂ emission during taxing, the amount of CO₂ emission from consuming 1kW electric power shown in Table 4.13 is used.

Here, economic cost along with electric power consumption occurs in two situations. Firstly, while purchasing electric power from electric power company, electric power rate charged by company is viewed as economic cost along with electric power consumption. Secondly, when electric power generated by PV is consumed by household, although no cost happens in reality, in this research, FIT price is considered as economic cost along with electric power consumption. The reason is that when surplus power generated by PV is consumed by household instead of selling it to electric power company, household cannot get that part of profit.

Total cost is calculated by adding direct economic cost along with electric power consumption to indirect economic cost of multiplying CO₂ emission by carbon tax.

Figure 5.1 shows the carbon tax design framework [22] used in this research. Firstly, it is assumed that 1kWh electric power is needed by household whether to purchase it from electric power company or generate it by PV. While choosing to purchase from electric power company, total cost is calculated by three steps. Firstly,
calculate life cycle CO₂ emission and purchasing cost of that 1kWh electric power. Then, multiply that amount of CO₂ emission by carbon tax designed in this section. Finally, add it to purchasing cost to get the total cost. While choosing to generate 1kWh electric power by PV, total cost is calculated by three steps as well. Firstly, calculate life cycle CO₂ emission and FIT selling cost of that 1kWh electric power. Then, multiply that amount of CO₂ emission by carbon tax designed in this section. Finally, add it to FIT selling cost to get the total cost. By comparing total cost of purchasing 1kWh electric power from electric power company with total cost of generating the same amount of electric power by PV, carbon tax is decided.

![Carbon Tax Design Framework](image)

**Figure 5.1 Carbon Tax Design Framework [22]**

### 5.2 Calculation of Carbon Tax

Carbon tax calculation formula is shown in Formula (20) based on framework in Figure 2. The left side of formula shows the total cost of the purchase from electric power company including carbon tax. The right side shows the total cost of consuming surplus electric power generated by PV in household. In this research, carbon tax takes the minimum value of \( \text{tax} \) that satisfies Formula (20).

\[
ECAVE + \text{tax} \cdot ESCO2 \geq FIT + \text{tax} \cdot PVCO2
\]  

(20)
All symbols are explained as follows.

\( ECAVE \) : average price of electric power rate [Yen/Wh]
\( tax \) : carbon tax [Yen/t-CO2]
\( ESCO2 \) : CO\(_2\) emission from electric power company’s power supply life cycles [t-CO2/Wh]
\( FIT \) : feed-in-tariff [Yen/Wh]
\( PVCO2 \) : CO\(_2\) emission from PV life cycles [t-CO2/Wh]

Table 5.1 shows the calculation results of each region. The reason why result in Hokkaido region is negative is that FIT price is lower than electric power rate in Hokkaido. Compared with other European countries as shown in Table 5.2 [73], although carbon tax in Kanto is much higher than Japan’s current tax, it is reasonable to use Kanto’s result for current situation. Here in Table 5.2, This Research (2017) means carbon tax used in this research for current case, and Japan means Japan’s carbon tax in reality.

### Table 5.1 Carbon Tax in Each Region

<table>
<thead>
<tr>
<th>Region</th>
<th>Carbon Tax [Yen/t-CO2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kyushu</td>
<td>14849.8</td>
</tr>
<tr>
<td>Kansai</td>
<td>13808.6</td>
</tr>
<tr>
<td>Kanto</td>
<td>5914.5</td>
</tr>
<tr>
<td>Tohoku</td>
<td>8473</td>
</tr>
<tr>
<td>Hokkaido</td>
<td>-1372</td>
</tr>
</tbody>
</table>

### Table 5.2 Comparison of Carbon Tax

<table>
<thead>
<tr>
<th>Country</th>
<th>Carbon Tax [Yen/kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>This Research (2017)</td>
<td>5914.5</td>
</tr>
<tr>
<td>Japan</td>
<td>289</td>
</tr>
<tr>
<td>Finland</td>
<td>7640 – 8170</td>
</tr>
<tr>
<td>Sweden</td>
<td>12640 – 15670</td>
</tr>
<tr>
<td>Denmark</td>
<td>3050</td>
</tr>
</tbody>
</table>
According to reference [74] [75] [76], future carbon tax assumptions are shown in Table 5.3. In this research, sustainable development scenario is considered as future cases. Therefore, carbon tax is assumed to be 7056 Yen/t-CO2 in 2025 and 11200 Yen/t-CO2 in 2030.

Table 5.3 Future Carbon Tax Assumptions by scenario
(Made by Author Based on Reference [74] [75] [76])

<table>
<thead>
<tr>
<th>Scenario</th>
<th>2025</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>New Policies Scenario [Yen/t-CO2]</td>
<td>2800</td>
<td>4144</td>
</tr>
<tr>
<td>Sustainable Development Scenario [Yen/t-CO2]</td>
<td>7056</td>
<td>11200</td>
</tr>
</tbody>
</table>
6. Simulation Results

This chapter explains simulation results of current and future cases, and makes discussions about them. With simulation results, household cost, CO\textsubscript{2} emission in current situation and future situations are calculated by Formula (21) (22) (23) respectively. In addition, in order to clarify the effects of the introduction of PV and battery system into a house and technology development on all stakeholders, electric power company cost is calculated by Formula (24) as well besides household cost and CO\textsubscript{2} emission. By inputting all the preconditions explained in Chapter 4 and Chapter 5 into evaluation model described in Chapter 3, optimization problem is solved and optimal values of design variables are acquired. In other words, optimal amount of electric power flowing among objects in Figure 3.2 is obtained from solving optimization problem. With optimal values of design variables, household cost, CO\textsubscript{2} emission in current and future scenarios, electric power company cost, and total costs in current and future scenarios are calculated by Formula (21) (22) (23) (24) (25) (26). Variables with * mark in all of these formulas are optimal values of design variables from solving optimization problem. For example, \(x_{1t}^*\) shows the optimal value of design variable \(x_{1t}\) explained in Chapter 3.

As explained in Section 3.3.2, in the optimization problem, \(\alpha\) shows the importance of household cost, \(\beta\) shows the importance of government cost, and \(1 - \alpha - \beta\) shows the importance of electric power company. By changing values of \(\alpha\) and \(\beta\), different simulation results can be analyzed by solving optimization problem. However, in this research, three weight coefficients are equally considered, which means that \(\alpha = \beta = 1 - \alpha - \beta = 1/3\).

\[
RCostH = \sum_{t=1}^{24}(EC_t \cdot (x_{2t}^* + x_{3t}^*) - FIT \cdot x_{1t}^*) + BUP \cdot x_6^* + CPV - SPV - SB
\]  

\[21\]

\[
RCO2C = \sum_{t=1}^{24}(ESCO2 \cdot (x_{2t}^* + x_{3t}^*) + BUCO2 \cdot x_{1t}^*) + PVCO2 \cdot PVSUM
\]  

\[22\]
\[ RCO2F = \sum_{t=1}^{24} \left( \sum_{i=1}^{5} EM_i \cdot EL_i \cdot (x_{2t}^* + x_{3t}^*) + BUCO2 \cdot x_{1t}^* \right) \]

\[ + PVCO2 \cdot PVSUM \]

(23)

\[ RCostE = \sum_{t=1}^{24} \left( (CBU + CEG - AVO) \cdot x_{1t}^* \right) \]

(24)

\[ TotalCostC = \alpha \cdot RCostH + \beta \cdot RCO2C + (1 - \alpha - \beta) \cdot RCostE \]

(25)

\[ TotalCostF = \alpha \cdot RCostH + \beta \cdot RCO2F + (1 - \alpha - \beta) \cdot RCostE \]

(26)

All symbols are explained as follows:

- **RCostH**: simulation result of household cost [Yen/day]
- **RCO2C**: simulation result of CO\(_2\) emission in the current scenario [t-CO\(_2\)/day]
- **RCO2F**: simulation results of CO\(_2\) emission in the future scenarios [t-CO\(_2\)/day]
- **RCostE**: simulation results of electric power company cost [Yen/day]
- **TotalCostC**: simulation result of total cost in the current scenario [Yen/day]
- **TotalCostF**: simulation results of total cost in the future scenarios [Yen/day]
- **EC\(_{t}\)**: electric power rate at time \(t\) [Yen/Wh]
- **FIT**: feed-in tariff [Yen/Wh]
- **BUP**: battery price [Yen/kWh]
- **CPV**: installation cost of PV [Yen]
- **SPV**: subsidy of PV [Yen]
- **SB**: subsidy of battery [Yen]
- **ESCO2**: life cycle CO\(_2\) emission from electric power company’s power supply [t-CO\(_2\)/Wh]
- **BUCO2**: life cycle CO\(_2\) emission from backup power supplies [t-CO\(_2\)/Wh]
- **PVCO2**: life cycle CO\(_2\) emission from PV [t-CO\(_2\)/Wh]
- **PVSUM**: total electric power generated by PV [Wh]
- **EM\(_i\)**: Composition ratio of power supply \(i\) [%]
$EL_i$: life cycle CO$_2$ emission from power supply $i$ [t-CO2/Wh]
$CBU$: running cost of backup power supplies [Yen/Wh]
$CEG$: system enhance cost dealing with the selling of surplus electric power [Yen/Wh]
$AVO$: avoidable cost [Yen]

### 6.1 Results of Current Scenario

In this research, the optimal capacity of the battery system installed into a house with PV in each region is suggested considering total costs of all stakeholders. Furthermore, when that battery system and PV are implemented in the house, the changes of electric-power-related costs and CO$_2$ emission are quantified. In this section, the simulation results in present scenario including household cost, CO$_2$ emission and electric power company cost in all regions are explained. BAU in all figures means Business As Usual, which refers to households without PV or batteries. In other words, in BAU case, the electric power consumed by households is purchased from electric power companies only.

#### 6.1.1 Optimal Capacity of Battery Introduced

Simulation results of optimal capacity of battery ($x^*_i$ in Formula (21)) installed into a house in every region are shown in Table 6.1. It can be seen that except Kyushu region, optimal capacities of battery installed in to a house in all other regions are 0 kWh, which means that battery is not recommended considering all stakeholders’ cost because of high battery cost. However, 2 kWh battery is suggested in Kyushu region, and there are two possible reasons to explain it. Firstly, compared with other regions, there is most abundant solar irradiance in Kyushu region leading to largest amount of electric power generated by PV, which means most amount of surplus power is potentially to be generated in Kyushu region. In order to deal with surplus power, battery is introduced. Secondly, decent subsidy of battery is provided in Kyushu region, which decreases cost.
Table 6.1 Optimal Capacity of Battery Installed into a House in 2017

<table>
<thead>
<tr>
<th>Region</th>
<th>Kyushu</th>
<th>Kansai</th>
<th>Kanto</th>
<th>Tohoku</th>
<th>Hokkaido</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery Capacity [kWh]</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

6.1.2 Results of Household Cost

Simulation results of household cost in all regions are shown in Figure 6.1 ~ Figure 6.5. As explained in Section 6.1.1, in all regions besides Kyushu region, no battery system is installed into a house, which means that all of the surplus power generated is sold to electric power company. In Kyushu region, with 2 kWh battery installed into a house, surplus power generated by PV is store to battery or sold to electric power company. From Figure 6.1 ~ Figure 6.5, it can be seen that in all regions, household cost decreases with PV or PV and battery system compared with BAU, the reason of which is that household gets profit by selling surplus power generated by PV.

![Figure 6.1 Results of Household Cost in Kyushu (2017)](image-url)
Figure 6.2 Results of Household Cost in Kansai (2017)

Figure 6.3 Results of Household Cost in Kanto (2017)
6.1.3 Results of CO₂ Emission

Simulation results of CO₂ emission in all regions are shown in Figure 6.6 ~ Figure 6.10. From Figure 6.6 ~ Figure 6.10, it can be seen that in all regions, CO₂ emission
increases with PV or PV and battery system compares with BAU, the reason of which is that CO$_2$ emission from the running of backup battery in electric power company increases due to the selling of surplus power.

Figure 6.6 Results of CO$_2$ Emission in Kyushu (2017)

Figure 6.7 Results of CO$_2$ Emission in Kansai (2017)
Figure 6.8 Results of CO₂ Emission in Kanto (2017)

Figure 6.9 Results of CO₂ Emission in Tohoku (2017)
6.1.4 Results of Electric Power Company Cost

Simulation results of electric power company cost in all regions are shown in Figure 6.11 ~ Figure 6.15. From Figure 6.11 ~ Figure 6.15, it can be seen that in all regions, electric power company cost increases with PV or PV and battery system compares with BAU. Here, electric power company cost in BAU case is 0 because system stabilization cost does not occur with the purchase of electric power from electric power company.
Figure 6.11 Results of Electric Power Company Cost in Kyushu (2017)

Figure 6.12 Results of Electric Power Company Cost in Kansai (2017)
Figure 6.13 Results of Electric Power Company Cost in Kanto (2017)

Figure 6.14 Results of Electric Power Company Cost in Tohoku (2017)
6.1.5 Results of Total Cost

Figure 6.16 shows the simulation results of total cost in all regions in 2017. Compared with BAU cases, total cost in the current scenario is higher in Kyushu, Kansai and Hokkaido regions. In Kanto and Tohoku regions, total cost in the current scenario is around 1 yen/day lower than the BAU case. The electric power charge in these two regions are the highest among other regions. Since households do not have to purchase the amount of electric power generated by PV from electric power companies, household cost decreases a lot. Although the weight coefficients of household cost, government cost and electric power company cost are the same, household cost makes the largest effect on the total cost because of the largest value of household cost among government and electric power company cost. That is the reason why the total cost in the current scenario is lower than the BAU case in Kanto and Tohoku regions.
6.2 Results of Future Scenarios

As explained in Section 6.1, high battery cost influences the economic and environmental effect of PV system on stakeholders a lot. It is known that battery cost decreases with technology development. Furthermore, power generation efficiency of PV, charge/discharge efficiency of battery and other changes along with technology development as well, which might lead to totally different results. Therefore, future development of technology is considered in this research. Since it is difficult to predict how fast technology develops in the future, three cases of technology development are considered in this research, which are low, standard and high technology levels. This section explains simulation results in 2025 and in 2030 with changed values of constants described in Chapter 4.

6.2.1 Optimal Capacity of Battery Introduced

Simulation results of optimal capacity of battery ($x^*_6$ in Formula (21)) installed into a house in every region are shown in Table 6.2. Low, Standard, High in Table 6.2 mean low, standard and high technology level respectively. Compared with current case

Figure 6.16 Results of Total Cost (2017)
explained in Section 6.1.1, it can be seen that battery system is suggested to be install into existing houses in all region. In addition, the higher technology level is, the larger capacity of battery installed will be. Two possible reasons can explain this phenomenon. Firstly, with higher power generation efficiency of PV, more electric power is generated by PV, which triggers larger capacity of battery to be installed into a house in order to solve surplus power problem. Secondly, lower battery price lowers total stakeholders’ cost.

Table 6.2 Optimal Capacity of Battery Installed into a House in 2025 and 2030

<table>
<thead>
<tr>
<th>Battery Capacity [kWh]</th>
<th>2025</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>Standard</td>
</tr>
<tr>
<td>Kyushu</td>
<td>14</td>
<td>16</td>
</tr>
<tr>
<td>Kansai</td>
<td>14</td>
<td>16</td>
</tr>
<tr>
<td>Kanto</td>
<td>12</td>
<td>17</td>
</tr>
<tr>
<td>Tohoku</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Hokkaido</td>
<td>11</td>
<td>12</td>
</tr>
</tbody>
</table>

6.2.2 Results of Household Cost

Simulation results of household cost in all regions are shown in Figure 6.17 ~ Figure 6.21. Low Level, Standard Level and High Level are houses with both PV and battery of optimal capacity shown in Table 6.2. For example, in Figure 6.17, Low Level in 2025 means houses with PV and 14 kWh battery, Standard Level in 2025 means houses with PV and 16 kWh battery, and High Level means houses with PV and 19 kWh battery.

From Figure 6.17 ~ Figure 6.21, it can be seen that in all regions, household cost decreases with PV and battery introduced into a house compared with BAU in both 2025 and 2030.

From Figure 6.17 ~ Figure 6.20, in Kyushu, Kansai, Kanto and Tohoku region, under same technology level, household cost in 2030 is lower than that in 2025 because of decreasing introduction price of PV and battery. However, from Figure 6.21, it can be seen that in Hokkaido region, under low and standard level of technology, household cost in 2030 is higher than that in 2025. The reason is that the optimal capacity of battery’s gap between 2025 and 2030 is much larger than that in other regions, which means in 2025, total battery cost is much cheaper even with decreasing price per kWh. And the
reason why huge gap occurs is that as Hokkaido has the least amount of solar irradiance among all regions, with low and standard level of PV efficiency in 2025, electric power generated by PV is not that much, which makes the need for battery lower.

From Figure 6.17 ~ Figure 6.21, in both 2025 and 2030, the higher technology level is, the higher household cost will be. The reason is that with higher PV efficiency, more electric power is generated by PV. Therefore, in order to deal with increasing surplus power, larger capacity of battery is installed into a house, which leads to higher household cost.

![Figure 6.17 Results of Household Cost in Kyushu (2025 & 2030)](image-url)
Figure 6.18 Results of Household Cost in Kansai (2025 & 2030)

Figure 6.19 Results of Household Cost in Kanto (2025 & 2030)
Figure 6.20 Results of Household Cost in Tohoku (2025 & 2030)

Figure 6.21 Results of Household Cost in Hokkaido (2025 & 2030)
6.2.3 Results of CO\textsubscript{2} Emission

Simulation results of CO\textsubscript{2} emission in all regions are shown in Figure 6.22 ~ Figure 6.26. Low Level, Standard Level and High Level are houses with both PV and battery of optimal capacity shown in Table 6.2.

From Figure 6.22 ~ 6.26, it can be seen that in all regions, CO\textsubscript{2} emission decreases compared with BAU in both 2025 and 2030 because of less surplus power that leads to less CO\textsubscript{2} emission from the running of backup battery in electric power company. Furthermore, in all regions, under the same technology level, CO\textsubscript{2} emission in 2030 is lower than that in 2025, because of the change of power supply composition ratio as one of the reasons. And another reason is that with larger capacity of battery installed into a house in 2030, CO\textsubscript{2} emission from backup battery decreases.

However, the relation between technology level and CO\textsubscript{2} emission differs from region to region. The tendencies are explained by region below.

In Kyushu region, from Figure 6.22, it shows that the higher the technology level is, the more CO\textsubscript{2} emission will be in both 2025 and 2030. Specific reasons are explained based on Formula (23) and summarized in Table 6.3. In Formula (23), it shows that total CO\textsubscript{2} emissions consist of CO\textsubscript{2} emission from the purchase of electric power company, backup battery and power generation from PV.

In 2025, with technology development, electric power generated by PV (\textit{PVSUM} in Formula (23)) increases because of higher PV efficiency. Therefore, CO\textsubscript{2} emission from power generation by PV increases. In addition, with more power generated by PV, electric power purchased from electric power company (\(x^{2}_{2t} + x^{2}_{3t}\) in Formula (23)) decreases, which means CO\textsubscript{2} emission from the purchase of electric power company decreases. Furthermore, with larger capacity of battery, surplus power sold to electric power company (\(x^{3}_{1t}\) in Formula (23)) decreases, so CO\textsubscript{2} emission from backup battery decreases. As total increasing part is larger than decreasing part, total CO\textsubscript{2} emissions increase.

In 2030, different from 2025, surplus power sold to electric power company increases because PV generates so much electric power that even larger capacity of battery cannot solve all of it. Thus, CO\textsubscript{2} emission from backup battery increases. As total increasing part is larger than decreasing part, total CO\textsubscript{2} emissions increase.
Table 6.3 CO\textsubscript{2} Emission Analysis in 2025 and 2030 (Kyushu)

<table>
<thead>
<tr>
<th></th>
<th>2025</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO\textsubscript{2} emission from power generation by PV</td>
<td>Increase</td>
<td>Increase</td>
</tr>
<tr>
<td>CO\textsubscript{2} emission from purchase of electric power</td>
<td>Decrease</td>
<td>Decrease</td>
</tr>
<tr>
<td>CO\textsubscript{2} emission from backup battery</td>
<td>Decrease</td>
<td>Increase</td>
</tr>
<tr>
<td>Total CO\textsubscript{2} emissions</td>
<td>Increase</td>
<td>Increase</td>
</tr>
</tbody>
</table>

In Kansai region, from Figure 6.23, it shows that the higher the technology level is, the less CO\textsubscript{2} emission will be in 2025, but the more CO\textsubscript{2} emission will be in 2030. Specific reasons are explained based on Formula (23) and summarized in Table 6.4.

In 2025, with technology development, electric power generated by PV ($PVSUM$ in Formula (23)) increases because of higher PV efficiency. Therefore, CO\textsubscript{2} emission from power generation by PV increases. In addition, with more power generated by PV, electric power purchased from electric power company ($x_{2t}^* + x_{3t}^*$ in Formula (23)) decreases, which means CO\textsubscript{2} emission from the purchase of electric power company decreases. Furthermore, with larger capacity of battery, surplus power sold to electric
power company \( (x^2_t \text{ in Formula (23)}) \) decreases, so CO\(_2\) emission from backup battery decreases. As total increasing part is smaller than decreasing part, total CO\(_2\) emissions decrease.

In 2030, different from 2025, there is no surplus power sold to electric power company in all technology levels. Thus, CO\(_2\) emission from backup battery remains 0. As total increasing part is larger than decreasing part, total CO\(_2\) emissions increase.

![Figure 6.23 Results of CO\(_2\) Emission in Kansai (2025 & 2030)](image)

**Table 6.4 CO\(_2\) Emission Analysis in 2025 and 2030 (Kansai)**

<table>
<thead>
<tr>
<th>Year</th>
<th>2025</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO(_2) emission from power generation by PV</td>
<td>Increase</td>
<td>Increase</td>
</tr>
<tr>
<td>CO(_2) emission from purchase of electric power</td>
<td>Decrease</td>
<td>Decrease</td>
</tr>
<tr>
<td>CO(_2) emission from backup battery</td>
<td>Decrease</td>
<td>Remain</td>
</tr>
<tr>
<td>Total CO(_2) emissions</td>
<td>Decrease</td>
<td>Increase</td>
</tr>
</tbody>
</table>
In Kanto region, from Figure 6.24, it shows that the higher the technology level is, the more CO\textsubscript{2} emission will be in both 2025 and 2030. Specific reasons are explained based on Formula (23) and summarized in Table 6.5.

From low to standard technology level in 2025, surplus power decreases to 0, therefore CO\textsubscript{2} emission from backup battery decreases a lot, which explains the high CO\textsubscript{2} emission under low technology level in 2025.

In 2025 (standard and high level) and 2030, with technology development, electric power generated by PV (\textit{PVSUM} in Formula (23)) increases because of higher PV efficiency. Therefore, CO\textsubscript{2} emission from power generation by PV increases. In addition, with more power generated by PV, electric power purchased from electric power company (\textit{x}_{A} + \textit{x}_{B} in Formula (23)) decreases, which means CO\textsubscript{2} emission from the purchase of electric power company decreases. Furthermore, there is no surplus power sold to electric power company (\textit{x}_{i} in Formula (23)) in all technology levels. Thus, CO\textsubscript{2} emission from backup battery remains 0. As total increasing part is larger than decreasing part, total CO\textsubscript{2} emissions increase.

![Figure 6.24 Results of CO\textsubscript{2} Emission in Kanto (2025 & 2030)](image_url)
Table 6.5 CO₂ Emission Analysis in 2025 and 2030 (Kanto)

<table>
<thead>
<tr>
<th></th>
<th>2025 (Low → Standard)</th>
<th>2025 (Standard → High) &amp; 2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emission from power generation by PV</td>
<td>Increase</td>
<td>Increase</td>
</tr>
<tr>
<td>CO₂ emission from purchase of electric power</td>
<td>Decrease</td>
<td>Decrease</td>
</tr>
<tr>
<td>CO₂ emission from backup battery</td>
<td>Decrease</td>
<td>Remain</td>
</tr>
<tr>
<td>Total CO₂ emissions</td>
<td>Decrease</td>
<td>Increase</td>
</tr>
</tbody>
</table>

In Tohoku region, from Figure 6.25, it shows that the higher the technology level is, the less CO₂ emission will be in both 2025 and 2030. Specific reasons are explained based on Formula (23) and summarized in Table 6.6.

In both 2025 and 2030, with technology development, electric power generated by PV ($PVSUM$ in Formula (23)) increases because of higher PV efficiency. Therefore, CO₂ emission from power generation by PV increases. In addition, with more power generated by PV, electric power purchased from electric power company ($x_{2t}^* + x_{3t}^*$ in Formula (23)) decreases, which means CO₂ emission from the purchase of electric power company decreases. Furthermore, there is no surplus power sold to electric power company ($x_{1t}^*$ in Formula (23)) in all technology levels. Thus, CO₂ emission from backup battery remains 0. As total increasing part is smaller than decreasing part, total CO₂ emissions decrease.
Table 6.6 CO₂ Emission Analysis in 2025 and 2030 (Tohoku)

<table>
<thead>
<tr>
<th>Year</th>
<th>2025 &amp; 2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emission from power generation by PV</td>
<td>Increase</td>
</tr>
<tr>
<td>CO₂ emission from purchase of electric power</td>
<td>Decrease</td>
</tr>
<tr>
<td>CO₂ emission from backup battery</td>
<td>Remain</td>
</tr>
<tr>
<td>Total CO₂ emissions</td>
<td>Decrease</td>
</tr>
</tbody>
</table>

In Hokkaido region, from Figure 6.26, CO₂ emissions under low and standard technology level are much higher than that under high level in 2025 because of large amount of surplus power as explained in Section 6.2.2. Besides, in 2030, although CO₂ emission has increasing tend along with technology development, it does not make many differences.
6.2.4 Results of Electric Power Company Cost

Simulation results of electric power company cost in all regions are explained in this section.

In Kyushu region, from Figure 6.27, electric power company cost decreases along with technology development in 2025, but the tendency is opposite in 2030. In 2025, with higher technology level, larger capacity of battery is installed into a house to deal with surplus power problem, which leads to lower electric power company cost. However, compared with other regions, there is the most abundant solar irradiance, where the most amount power can be generated by PV. In 2030, with higher technology level, power generated by PV is too much to be just stored in battery. Therefore, surplus power increases, which leads to increasing electric power company cost.
Figure 6.27 Results of Electric Power Company Cost in Kyushu (2025 & 2030)

In Kansai region, from Figure 6.28, it shows that in 2025, electric power company cost is higher than BAU, and it decreases along with technology development due to the decreasing surplus power. In 2030, electric power company cost is the same as BAU because there is no surplus power sold to electric power company.

Figure 6.28 Results of Electric Power Company Cost in Kansai (2025 & 2030)
In Kanto region, from Figure 6.29, it can be seen that only under low technology development level in 2025, electric power company cost is higher than BAU because there is still surplus power sold to electric power company.

![Figure 6.29 Results of Electric Power Company Cost in Kanto (2025 & 2030)](image)

In Tohoku region, under all levels of technology in both 2025 and 2030, since no surplus power sold to electric power company exists, electric power company cost is 0. Compared with other regions, since household electric power demand is the highest in Tohoku region as explained in Section 4.1, even with more power generated by PV, there is no surplus power sold to electric power company.

In Hokkaido region, from Figure 6.30, electric power company cost is quite high under low and standard technology level in 2025 because of large amount of surplus power generated by PV. Under high technology level in 2025 and all levels in 2030, electric power company cost is almost 0.
6.2.5 Results of Total Cost

Figure 6.31 ~ Figure 6.35 show the simulation results of total cost in all regions in 2025 and 2030. In all regions, and in both 2025 and 2030, total cost in households with PV and battery system is lower than BAU cases. In addition, from Figure 6.31 ~ Figure 6.33 and Figure 6.35, in Kyushu, Kansai, Kanto and Hokkaido regions, the higher technology level is, the higher total cost will be in both 2025 and 2030. The biggest reason is the increase of household cost as explained in Section 6.2.2. However, from Figure 6.34, in Tohoku region, the higher technology level is, the lower total cost will be in 2025. The reason is that household electric power consumption in Tohoku region is the highest among other regions, where higher PV efficiency can meet the need. When PV efficiency is so high that surplus power has to be sold to the electric power company, and larger capacity of battery needs to be installed, total cost of households increases. That is the reason why the total cost of high technology level in 2030 is higher than low and standard levels.
Figure 6.31 Results of Total Cost in Kyushu (2025 & 2030)

Figure 6.32 Results of Total Cost in Kansai (2025 & 2030)
Figure 6.33 Results of Total Cost in Kanto (2025 & 2030)

Figure 6.34 Results of Total Cost in Tohoku (2025 & 2030)
Figure 6.35 Results of Total Cost in Hokkaido (2025 & 2030)
7. Discussions

7.1 Discussions about Current Scenario

In the current scenario (2017), the simulation results show the reduction of household cost, but increases of CO$_2$ emission and electric power company cost in the houses with PV and battery systems. The reason why CO$_2$ emission and the electric power company cost increase is that as a large amount of surplus power is sold to the electric power company, the running of backup batteries in the company causes increasing CO$_2$ emission and system stabilization costs to the electric power company. And the reason why surplus power problems occur is because of the high introduction price of batteries in the present, which results in no battery system or only small capacity of battery system installed into the house.

Furthermore, as explained in Section 6.1.5, the total costs of households with PV are higher than that of households without PV in Kyushu, Kansai and Hokkaido regions, and only around 1 Yen/day reduction of total costs with PV takes place in Kanto and Tohoku regions.

Considering the benefits of all stakeholders and the changes of total costs, the implementation of PV and battery systems is not recommended for households in all five regions.

7.2 Discussions about Future Scenarios

In the future scenarios (2025 & 2030), the simulation results show the reduction of both household cost and CO$_2$ emission in the houses with PV and battery systems in all the five regions. The reason why CO$_2$ emission decreases is that most or all of the surplus power generated by PV is stored in the battery system in the household instead of being sold to the electric power company, which leads to the decreasing CO$_2$ emission from the backup battery in the electric power company. However, the electric power company cost increases because there is still surplus power being sold to the electric power company in some scenarios. In addition, as explained in Section 6.2.5, the total costs of households with PV and battery systems are lower than that of households without PV or battery system in all regions and in both 2025 and 2030. From the above,
the introduction of PV and battery systems is recommended for all the five regions, and the specific suggestions for each region will be explained in Chapter 8.

However, the results also show that the higher technology level is, the higher total costs will be in all the regions except Tohoku region. With higher technology level, the power generation efficiency of PV is higher. In this research, since the capacity of PV installed in all the five regions are all the same which is 4kW, more electric power is generated by PV with higher efficiency. However, when the power generated by PV is much larger than the household demand, the surplus power that cannot be fully stored into the battery system will be sold to the electric power company, which increases CO₂ emission on the contrary. This situation does not happen in Tohoku region because of the highest household electric power demand in Tohoku region among the remaining four regions. Therefore, the changes of PV capacity should have been taken into consideration in regard to the electric power consumption in households of different regions. Furthermore, from the analysis of CO₂ emission changes in Section 6.2.3, the CO₂ emission from power generation by PV cannot be overlooked. However, the changes of efficiency and price of PV but CO₂ emission from power generation by PV are considered. The development of technology related to CO₂ emission from power generation by PV might further decrease total CO₂ emissions.
8. Conclusions

This research built an economic and environmental optimization model for household energy-saving upgrades. It considered the requirements of three stakeholders: household, government, and electric power company. By inputting the data from references like household electric power consumption, electric power generated by PV, etc., the model quantified the electric-power-related cost including the household cost and the electric power company cost, and CO$_2$ emission. According to analysis of simulation results, the best collaborations between PV and the battery system have been suggested for all regions, and they are described in the following.

In the present scenario (2017), it is suggested that neither PV nor the battery system should be installed into houses in any regions.

In the future scenarios (2025), the values of FIT are predicted as 15.85Yen/kWh, 14Yen/kWh and 11.5Yen/kWh reflecting low, standard and high levels of technology development respectively. The efficiencies of PV are assumed as 23%, 25% and 28% respectively. The suggestions for the best collaboration between PV and the battery system are described in the following.

For Kyushu region:
- when FIT is 15.85Yen/kWh, the suggestion is to install 4kW PV (23% efficiency) and 14kWh battery
- when FIT is 14Yen/kWh, the suggestion is to install 4kW PV (25% efficiency) and 16kWh battery
- when FIT is 11.5Yen/kWh, the suggestion is to install 4kW PV (28% efficiency) and 19kWh battery

Among above three cases, the first one (FIT is 15.85Yen/kWh) can achieve the lowest total cost.

For Kansai region:
- when FIT is 15.85Yen/kWh, the suggestion is to install 4kW PV (23% efficiency) and 14kWh battery
- when FIT is 14Yen/kWh, the suggestion is to install 4kW PV (25% efficiency) and 16kWh battery
• when FIT is 11.5Yen/kWh, the suggestion is to install 4kW PV (28% efficiency) and 19kWh battery

Among above three cases, the first one (FIT is 15.85Yen/kWh) can achieve the lowest total cost.

For Kanto region:
• when FIT is 15.85Yen/kWh, the suggestion is to install 4kW PV (23% efficiency) and 12kWh battery
• when FIT is 14Yen/kWh, the suggestion is to install 4kW PV (25% efficiency) and 17kWh battery
• when FIT is 11.5Yen/kWh, the suggestion is to install 4kW PV (28% efficiency) and 20kWh battery

Among above three cases, the first one (FIT is 15.85Yen/kWh) can achieve the lowest total cost.

For Tohoku region:
• when FIT is 15.85Yen/kWh, the suggestion is to install 4kW PV (23% efficiency) and 15kWh battery
• when FIT is 14Yen/kWh, the suggestion is to install 4kW PV (25% efficiency) and 15kWh battery
• when FIT is 11.5Yen/kWh, the suggestion is to install 4kW PV (28% efficiency) and 17kWh battery

Among above three cases, the third one (FIT is 11.5Yen/kWh) can achieve the lowest total cost.

For Hokkaido region:
• when FIT is 15.85Yen/kWh, the suggestion is to install 4kW PV (23% efficiency) and 11kWh battery
• when FIT is 14Yen/kWh, the suggestion is to install 4kW PV (25% efficiency) and 12kWh battery
• when FIT is 11.5Yen/kWh, the suggestion is to install 4kW PV (28% efficiency) and 20kWh battery

Among above three cases, the first one (FIT is 15.85Yen/kWh) can achieve the lowest total cost.

In the future scenario (2030), the values of FIT are predicted as 7Yen/kWh, 4Yen/kWh and 0Yen/kWh reflecting low, standard and high levels of technology development respectively. The efficiencies of PV are assumed as 25%, 30% and 35% respectively. The suggestions for the best collaboration between PV and the battery system are described in the following.

For Kyushu region:
• when FIT is 7Yen/kWh, the suggestion is to install 4kW PV (25% efficiency) and 17kWh battery
• when FIT is 4Yen/kWh, the suggestion is to install 4kW PV (30% efficiency) and 22kWh battery
• when FIT is 0Yen/kWh, the suggestion is to install 4kW PV (35% efficiency) and 27kWh battery

Among above three cases, the first one (FIT is 7Yen/kWh) can achieve the lowest total cost.

For Kansai region:
• when FIT is 7Yen/kWh, the suggestion is to install 4kW PV (25% efficiency) and 18kWh battery
• when FIT is 4Yen/kWh, the suggestion is to install 4kW PV (30% efficiency) and 23kWh battery
• when FIT is 0Yen/kWh, the suggestion is to install 4kW PV (35% efficiency) and 28kWh battery

Among above three cases, the first one (FIT is 7Yen/kWh) can achieve the lowest total cost.

For Kanto region:
• when FIT is 7Yen/kWh, the suggestion is to install 4kW PV (25% efficiency) and 18kWh battery

• when FIT is 4Yen/kWh, the suggestion is to install 4kW PV (30% efficiency) and 23kWh battery

• when FIT is 0Yen/kWh, the suggestion is to install 4kW PV (35% efficiency) and 28kWh battery

Among above three cases, the first one (FIT is 7Yen/kWh) can achieve the lowest total cost.

For Tohoku region:
• when FIT is 7Yen/kWh, the suggestion is to install 4kW PV (25% efficiency) and 18kWh battery

• when FIT is 4Yen/kWh, the suggestion is to install 4kW PV (30% efficiency) and 20kWh battery

• when FIT is 0Yen/kWh, the suggestion is to install 4kW PV (35% efficiency) and 25kWh battery

Among above three cases, the second one (FIT is 4Yen/kWh) can achieve the lowest total cost.

For Hokkaido region:
• when FIT is 7Yen/kWh, the suggestion is to install 4kW PV (25% efficiency) and 18kWh battery

• when FIT is 4Yen/kWh, the suggestion is to install 4kW PV (30% efficiency) and 23kWh battery

• when FIT is 0Yen/kWh, the suggestion is to install 4kW PV (35% efficiency) and 28kWh battery

Among above three cases, the first one (FIT is 7Yen/kWh) can achieve the lowest total cost.
References


97


[66] Agency for Natural Resources and Energy, "Related Document about the Outlook of Long-Term Energy Demand (translated by author)," 2015.


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Appendix

The following is the MATLAB code.

```matlab
format long;

% setting of t
time=24;

% amount of x which is dependent on t
length=5;

% electric power charge [Yen/Wh] Tokyo
EC=ones(1,24);
EC(1:6)=EC(1:6)*0.021;
EC(6:22)=EC(6:22)*0.032;
EC(23:end)=EC(23:end)*0.021;

% FIT [Yen/Wh]
FIT=ones(1,time)*30/1000;  % 2017

FIT=ones(1,time)*11.5/1000;  % 2025 High
FIT=ones(1,time)*14/1000;  % 2025 Standard
FIT=ones(1,time)*15.85/1000;  % 2025 Low

FIT=zeros(1,time);  % 2030 High
FIT=ones(1,time)*4/1000;  % 2030 Standard
FIT=ones(1,time)*7/1000;  % 2030 Low

% PV parameters

PV_VOL=4;  % PV volume [kW]
PV_UA=1.63/0.345;  % Panel’s area per 1kW [m2/kW]

PV_EFF=0.212; % PV efficiency [%] 2017
%PV_EFF=0.28; % PV efficiency [%] 2025 High
%PV_EFF=0.25; % PV efficiency [%] 2025 Standard
%PV_EFF=0.23; % PV efficiency [%] 2025 Low

%PV_EFF=0.35; % PV efficiency [%] 2030 High
%PV_EFF=0.3; % PV efficiency [%] 2030 Standard
%PV_EFF=0.25; % PV efficiency [%] 2030 Low

C_PV=371000*PV_VOL/10/365; % PV Cost [Yen] 2017
%C_PV=171000*PV_VOL/10/365; % PV Cost [Yen] 2025
%C_PV=121000*PV_VOL/10/365; % PV Cost [Yen] 2030

S_PV=0.2*C_PV; % Subsidy [Yen] 2017 Tokyo
%S_PV=0.2*C_PV/2; % Subsidy [Yen] 2025 Tokyo
% No subsidy in 2030

% Battery parameters

PCSB = 2 / 4.8; % [kW/kWh]

BUP = 150000 / 10 / 365; % Battery cost [Yen/kWh] 2017
%BUP = 30000 / 10 / 365; % Battery cost [Yen/kWh] 2025
%BUP = 15000 / 10 / 365; % Battery cost [Yen/kWh] 2030

alpha = 0.85; % charge efficiency 2017
%alpha = 0.95; % charge efficiency 2025
%alpha = 0.99; % charge efficiency 2030
beta = 1 / alpha; % discharge efficiency

% CO2 emission parameters

% ESCO2 [t-CO2/Wh] 2017 Tokyo
ESCO2 = 0.463; % [kg-CO2/kWh]
ESCO2 = ESCO2 / 1000000; % [t-CO2/Wh]
ESCO2 [t-CO2/Wh] future  

Composition ratio of power supplies [Coal, LNG, Petroleum, Renewable Energy, Nuclear]  
%EM = [0.293,0.351,0.0335,0.1855,0.117]; % 2025  
%EM = [0.26,0.27,0.03,0.24,0.20]; % 2030  

Life cycle CO2 emission from power supplies [t-CO2/Wh]  
%EL = [943,(474+599)/2,738,(11+13+38+26)/2,19]; %[g-CO2/kWh]  
%EL = EL/1000000000;  

ESCO2 = EM * EL';  

Life cycle CO2 emission from backup battery [t-CO2/Wh]  
BUCO2 = 738; % [g-CO2/kWh] Petroleum  
BUCO2 = BUCO2 / 1000000000; %[t-CO2/Wh]  

Life cycle CO2 emission from PV [t-CO2/Wh]  
PVCO2 = 38; % [g-CO2/kWh]  
PVCO2 = PVCO2 / 1000000000; %[t-CO2/Wh]  

Carbon tax [Yen/t-CO2]  
FIT_AVE = mean(FIT); % average of FIT [Yen/Wh]  
EC_AVE = mean(EC); % average of electric power charge [Yen/Wh]  
tax = (FIT_AVE - EC_AVE) / (ESCO2 - PVCO2); %[Yen/t-CO2] 2017  

tax = 7056; %2025  
tax = 11200; %2030  

Running cost of backup battery in electric power company [Yen/Wh] Petroleum  
CBU = 22.1/1000;  

Avoidable cost [Yen/Wh] Tokyo
AVO = 0.01025;

% System Stabilization Cost [Yen/Wh]
CEG = 0.8/1000;  %2017
%CEG = 8 / 1000;  %2025
%CEG = 10/1000;  %2030

% the way to calculate household electric power consumption is written in thesis
% Input electric power consumption per hour into the following Dem
Dem = demand_tokyo;  % get data from variables from another work space
Dem=Dem';  %[Wh]

% calculation of electric power generated by PV
INS = irradiance_tokyo;  % get data from variables from another work space [Wh/m2]
PV = zeros(1,time);
for t = 1:time
    PV(t) = INS(t) * PV_EFF * PV_UA * PV_VOL;
end
PV = PV';  %[Wh]

% design variables [Wh]
x= sym('x',[time,length]);
x= x.;
x= x(:,);
x(end+1) = sym('x6');

% definition of PV2H [Wh]
PVtoH = zeros(time,1);
for t = 1:time
    if PV(t) >= Dem(t)
        PVtoH(t) = Dem(t);
    else
        PVtoH(t) = PV(t);
    end
% Definition of remaining capacity of battery in the previous day
SOC_start = 0.15; % ratio of remaining in the previous day
SOC_Bat_Before = 1000 * x(end) * SOC_start; %[Wh]

% Definition of charging state
SOC_Bat = sym(zeros(time,1));
SOC_Bat_0 = SOC_Bat_Before;

% Constraints

% linear equality constraint: formula (9) 'SOC_Bt = SOC_Bt-1 + alpha * (x3t + x4t) - beta* x5t'
for i=1:time
SOC_Bat(i) = SOC_Bat_Before + alpha * (x(length*i-(length-3)) + x(length*i-(length-4))) - beta * x(length*i-(length-5));
SOC_Bat_Before =SOC_Bat(i);
end

% get Matrix ‘Aeq’ and Vector ‘beq’ in linear equality constraints 'Aeq*x=beq' formula (6) (7) (8)
aeq1 = [1 0 0 1 0 ];
aeq2 = [0 1 0 0 1 ];
aeq = [aeq1;aeq2];
Aeq = zeros(size(aeq,1) * time , size(x,1));
for i = 1:time
Aeq(size(aeq,1) * i - (size(aeq,1)-1) : size(aeq,1) * i , length * i - (length-1) : length * i) = aeq;
end
beq = zeros(size(aeq,1) * time , 1);
for i = 1:time
beq(size(aeq,1) * i - (size(aeq,1)-1) : size(aeq,1) * i , 1) = [PV(i)-PVtoH(i) ; Dem(i)-PVtoH(i)];
end

% inequality constraint1: formula (10) 'x3t + x4t + x5t <= PCSB * x6t * 1000'
a1=[0 0 1 1 1];
A1 = zeros(time,size(x,1));
for i = 1:time
    A1(i,size(a1,2)*i-(size(a1,2)-1):size(a1,2)*i)=a1;
    A1(i,size(A1,2))= -PCSB*1000;
end
b1 = zeros(time,1);

% inequality constraint2 : formula (11) 'x5t <= SOC_Bat(t)= SOC_Bat(t-1) + alpha*(x3t+x4t) - beta*x5t'
a2_1 = [0 0 -alpha -alpha 1+beta];
a2_2 = zeros(1,size(x,1));
a2_2_0 =[0 0 -alpha -alpha beta];
A2=zeros(time,size(x,1));
A2(1,1:size(a2_1,2))=a2_1;
A2(1,size(A2,2)) = -1000*SOC_start;
for i = 2:time
    a2_2(1,size(a2_2_0,2)*(i-1) - (size(a2_2_0,2)-1):size(a2_2_0,2)*(i-1))=a2_2_0;
    A2(i,1:size(a2_2,2)) = a2_2;
    A2(i,size(a2_1,2)*i - (size(a2_1,2)-1):size(a2_1,2)*i)=a2_1;
    A2(i,size(A2,2)) = -1000*SOC_start;
end
b2 = zeros(time,1);

% inequality constraint3 : formula (12) 'SOC_Bat_min <= SOC_Bat(t) '
a3_0 = [0 0 -alpha -alpha beta];
a3 = zeros(1,size(x,1));
A3 = zeros(time,size(x,1));
for i = 1:time
    a3(1,size(a3_0,2)*i-(size(a3_0,2)-1):size(a3_0,2)*i)=a3_0;
A3(i,1:size(a3,2))=a3;
end
b3 = zeros(time,1);

% inequality constraint4 : formula (12) 'SOC_Bat <= SOC_Bat_max'
a4_0 = [0 0 alpha alpha -beta];
a4 = zeros(1,size(x,1));
A4 = zeros(time,size(x,1));
for i = 1:time
    a4(1,size(a4_0,2)*i-(size(a4_0,2)-1):size(a4_0,2)*i)=a4_0;
    A4(i,1:size(a4,2))=a4;
    A4(i,size(A4,2))=(0.15-0.85)*1000;
end
b4 = zeros(time,1);

% get Matrix ‘A’ and Vector ‘b’ in linear inequality constraints ‘A*x<=b’
A = [A1;A2;A3;A4];
b = [b1;b2;b3;b4];

% solve optimization problem

% weight coefficients
h = 1/3;
g = 1/3;
e = (1 - h - g);

% Objective function
Cost = sym(0);
CostH = sym(0);
CostG = sym(0);
CostE = sym(0);
for i=1:time
cost_h = EC(i) * (x(length*i-(length-2)) + x(length*i-(length-3))) -FIT(i) * x(length*i-(length-1));
CostH = CostH + cost_h;
cost_g = tax * (ESCO2 * (x(length*i-(length-2)) + x(length*i-(length-3))) + BUCO2 * x(length*i-(length-1)));
CostG = CostG + cost_g;
cost_e = (CBU + CEG - AVO) * x(length*i-(length-1));
CostE = CostE + cost_e;
end
CostH = CostH + x(end) * BUP * 0.8 + C_PV - S_PV;  % 2017 tokyo subsidy
CostH = CostH + x(end) * BUP * 0.9 + C_PV - S_PV;  % 2025 tokyo subsidy
CostH = CostH + x(end) * BUP + C_PV;  % 2030 no tokyo subsidy
CostG = CostG + tax * PVCO2 * sum(PV);
Cost = h * CostH + g * CostG + e * CostE;

% get Vector ‘f’ representing objective
[coeffienct_obj,check_cost] = coeffs(Cost,x);
f = zeros(size(x,1),1);
if check_cost(end) == 1
    for s = 1 : size(check_cost,2)-1
        for u = 1 : size(x,1)
            if check_cost(s) == x(u)
                f(u) = double(coeffienct_obj(s));
            end
        end
    end
else
    for s = 1 : size(check_cost)
        for u = 1 : size(x,1)
            if check_cost(s) == x(u)
                f(u) = double(coeffienct_obj(s));
            end
        end
    end
end
end

% mixed-integer linear programming basics: solver-based
intcon = [time*length+1];  % Vector indicating variables that take integer values
lb = zeros(size(x,1),1);  % Vector of lower bounds
ub = Inf(time*length,1);  % Vector of upper bounds
ub(end+1) = 100;  % x6 is less or equal to 100
[xfinal,fval,exitflag,output] = intlinprog(f,intcon,A,b,Aeq,beq,lb,ub);

% Get optimal values of design variables
ans_xfinal = zeros(time+1,length);
for t = 1:time
    for i = 1:length
        ans_xfinal(t,i) = xfinal(length*(t-1)+i);
    end
end
ans_xfinal(time+1,1) = xfinal(end);

% optimal household cost, CO2 emission, electric power company cost
ans_cost_home = 0;  % household cost [Yen]
ans_CO2_home = 0;  % CO2 emission [t-CO2]
ans_cost_E = 0;  % electric power company cost [Yen]
for i=1:time
    ans_cost_h = EC(i) * (xfinal(length*i-(length-2)) + xfinal(length*i-(length-3))) -
    FIT(i) * xfinal(length*i-(length-1));
    ans_cost_home = ans_cost_home + ans_cost_h;
    ans_CO2 = ESCO2 * (xfinal(length*i-(length-2)) + xfinal(length*i-(length-3))) +
    BUCO2 * xfinal(length*i-(length-1));
    ans_CO2_home = ans_CO2_home + ans_CO2;
    ans_cost_e = (CBU + CEG - AVO) * xfinal(length*i-(length-1));
    ans_cost_E = ans_cost_E + ans_cost_e;
end
ans_cost_home = ans_cost_home + xfinal(end) * BUP * 0.8 + C_PV - S_PV;  % 2017

tokyo sb
%ans_cost_home = ans_cost_home + xfinal(end) * BUP * 0.9 + C_PV - S_PV; %2025

%ans_cost_home = ans_cost_home + xfinal(end) * BUP + C_PV; % 2030 no tokyo sb

ans_CO2_home = ans_CO2_home + PVCO2 * sum(PV);
ans_Cost = h * ans_cost_home + g * tax * ans_CO2_home + e * ans_cost_E;

% BAU(without PV or battery system)
ans_nosystem_cost = 0;
ans_nosystem_CO2 = 0;
for i = 1:time
    ans_nosystem_c = Dem(i) * EC(i);
    ans_nosystem_cost = ans_nosystem_cost + ans_nosystem_c;
    ans_nosystem_CO = ESCO2 * Dem(i);
    ans_nosystem_CO2 = ans_nosystem_CO2 + ans_nosystem_CO;
end
ans_nosystem_cost = ans_nosystem_cost;
ans_nosystem_CO2 = ans_nosystem_CO2;

result = zeros(1,size(ans_xfinal,2));
result(1:4) = [ans_cost_home,ans_CO2_home,ans_cost_E,ans_Cost];
result_nosystem = zeros(1,size(ans_xfinal,2));
result_nosystem(1:2) = [ans_nosystem_cost,ans_nosystem_CO2];

% output
xlswrite('tokyo_2017',[ans_xfinal;result;result_nosystem]);