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Joint Optimization Scheme of Electric Vehicles and Smart Home Energies Considering User Comfort Preference

By Liu Huan

A thesis submitted to
School of Information Science,
Japan Advanced Institute of Science and Technology,
in partial fulfillment of the requirements
for the degree of
Master of Information Science
Graduate Program in Information Science

Written under the direction of
Associate Professor Yuto Lim

March 2019

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and approved by
Associate Professor Yuto Lim
Professor Yasuo Tan
Professor Yoichi Shinoda
Research Associate Professor Razvan Florin Beuran

February, 2019 (Submitted)

Abstract

With the emergence of the problems, such as the aggravation of environment pollution, the shortage of non-renewable resources, and so on, a lot of renewable resources are incorporated into the power grid. Electric Vehicle (EV) as a new type of transportation, are becoming more and more popular because of their low pollution and low carbon emission characteristics and also because they reduce the dependency on fossil fuel which make a society more environmental and sustainable.

However, human EV activities will have a significant impact on the power distribution network (smart grid) and increase the home electricity cost if charging and discharging of EVs are not controlled appropriately. So, to solve these problems, it is necessary to analyze the residents' activities, battery storage, charging power level, charging time and so on.

In this thesis, I do a study of charging and discharging scheme of EV for smart homes. In the first chapter, I introduced the development of EV, which is the trend of near future. The objective of this research is to propose a joint optimization scheme for smart homes which can save cost as well as consider residents' comfort. Thus, the smart community simulator is necessary to analyze the daily consumption, residents' activities, the generation of PV and FC. The driving patterns of EV is also necessary.

Chapter 2 presents the introduction about smart home by defining smart home, discussing the components of smart home. In addition, with the development of EV, EV and V2H system are also introduced in this chapter.

Chapter 3 discusses the experiment environment. After the introductions of iHouse and smart community simulator, the models of renewable energy source, residents' activities, EV and home appliances are built.

Chapter 4 presents the objective functions and the constrain conditions. Based on the data of temperature and the PV, FC generation of iHouse, the joint optimization scheme is proposed.

Chapter 5 uses the numerical results of the scheme to analyze the necessity of ESS, EV. It will also let other researchers to further research the situation of multiple-household in a community and schedule other home appliances based on the proposed scheme.

Chapter 6 summarizes the works in this paper, draws contributions of ESS, EV and mentions the future work.

Keywords: smart homes, electric vehicle, user comfort.

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Chapter 1

Introduction

In this chapter, I introduce the background, objective, significance, method of this research and related works. The organization of this thesis is at the end of this chapter.

1.1 Research Background

With the emergence of the problems, such as the aggravation of environment pollution, the shortage of non-renewable resources, and so on, a lot of renewable resources are incorporated into the power grid.

EV as a new type of transportation, are becoming more and more popular because of their low pollution and low carbon emission characteristics and also because they reduce the dependency on fossil fuel which make a society more environmental and sustainable.

However, human EV activities will have a significant impact on the power distribution network (smart grid) and increase the home electricity cost if charging and discharging of EVs are not controlled appropriately. So, to solve these problems, it is necessary to analyze the residents' activities, battery storage, charging power level, charging time and so on.

1.2 Research Objective

In this research, the objective is to propose a joint optimization scheme for smart homes with the goal of improving residents' thermal comfort as well as reducing home electricity cost. For this purpose, the smart community simulator is used in this research to provide a feasible concept of smart micro-grid incorporating with the EVs and smart home energies. This smart community simulator can analyze when the smart home energies are in a short supply, the EV charging can be done when there is an adequate supply or the electricity price is low. By this way, it can not only save the home electricity cost, but also have a preferable benefit in improving the residents' comfort preference.

1.3 Research Significance

In this research, the proposed joint optimization scheme for smart home is coordinated the smart home energies and the EV to minimize the electricity cost and to meet all kinds of constraints and the residents' comfort demands can also be achieved. The proposed scheme can be a reference in the future home energy management system (HEMS) with its reliability and feasibility. The smart community simulator will play an important role in home electricity cost reduction, quality of human life improvement by guiding and controlling the operation of EV. In addition, the smart community simulator can be used to analyze the the driving patterns of EV, daily power consumption and so on in which these could give a positive significant of EV to our society toward the future smart grid. Through this way, the impact of EV can be reduced in terms of reducing charging cost, smoothing the load curve of the smart grid.

1.4 Research Method

First, I will understand and analyze the entire schematic of the smart community simulator. I will also confirm the operation of each component in smart community simulator. Second, I will analyze the driving patterns of EV , charging and discharging rules of EV, then construct a model of EV charging and discharging. Third, I will construct a model between EV and smart home battery storage, in which it can balance the energy during charging based on the residents' thermal comfort. Fourth, I will propose a charging scheme considering the electricity price in order to reduce the electricity cost. Fifth, I will analyze the influencing factors of residents' comfort, such as predictive mean value (PMV) and confirm the load that can improve the residents' comfort. Finally, I will propose a joint optimization scheme with the goal of improving residents' comfort as well as reducing electricity cost considering all kinds of constraints. I will analyze the results under three different ways as aforementioned third, fourth and fifth. I will also test and verify the effectiveness of the proposed joint optimization scheme.

1.5 Related Work

Some of the existing research works [1], [2] are mainly focused on the energy consumption and usage of EV in the smart grid at the theoretical and simulation studies and see the EV in the community as a whole to control the charging and discharging time. And paper [3], [4] proposed a joint scheduling scheme for EV and home appliances in the smart micro-grid and smart home environment. Paper [5] considered the residents' thermal comfort by using the price that aggregator has to pay when the temperature deviates from the desired temperature to compute the cost.

In this context, some studies [6], [7] show that the use of renewable energy source (RES) to charge the EV is feasible in the short term, and it can also reduce cost. However, these studies also point that, updates are necessary in the long term. Because the energy production from renewable sources, without smart charge, will not be able to meet the increased demand due to wildly use of EV.

The originality of this research is that the proposed joint optimization scheme of the EVs and smart home energies for smart homes focus on the single-household by using the smart community simulator, which is a feasible and futuristic conceptual model cooperated with all the components, such as EV, home appliances, residents' activities, solar photovoltaic

(PV), fuel cell (FC), and battery storage and use PMV parameters to improve residents' thermal comfort. Furthermore, the proposed joint optimization scheme will be more reliable and feasible to our smart grid community in the future.

1.6 Organization of this Thesis

The remainder of this thesis is organized as follows:

- Chapter 2

  Presents the introduction about smart home by defining smart home, discussing the components of smart home. In addition, with the development of EV, EV and V2H system are also introduced in this chapter.

- Chapter 3

  Discusses the experiment environment. After the introductions of iHouse and smart community simulator, the models of renewable energy source, residents' activities, EV and home appliances are built.

- Chapter 4

  Presents the objective functions and the constrain conditions. Based on the data of temperature and the PV, FC generation of iHouse, the charging and discharging scheme is proposed.

- Chapter 5

  Uses the numerical results of the scheme to analyze the necessity of ESS, EV. It will also let other researchers to further research the situation of multiple-household in a community and schedule other home appliances based on the proposed scheme.

- Chapter 6

  Summarizes the works in this paper, draws contributions of ESS, EV and mentions the future work.

Chapter 2

Smart Home and Electric Vehicle

In this chapter, I introduce the necessary knowledge of smart home, EV and components of EV to home (V2H) systems.

The first section introduces the basic information of smart home. The second section is about the background of smart home. The third section introduces the key components of smart home. The HVAC and V2H system which are used in this research are also introduced in the end of this section. The last section introduces the basic information of EV. Based on these techniques, it can provide the possibility for the widespread development of EV and it is the inevitable trend of future smart grid.

2.1 Introduction of Smart Home

Smart home is a residential platform that integrates home-related facilities with generic cabling technology, network communication technology, security technology, automatic control technology, audio and video technology to build efficient residential facilities and homes. The main target of smart home is to improve home safety, convenience, comfort, and artistry, and realize an environmentally friendly and energy-saving living environment. Smart home is usually understood as home automation, but more than automation.

Figure 2.1: Typical smart home appliances

2.2 Background of Smart Home

The concept of smart home was presented very early, but there has been no specific architectural case until 1984. And in the last few years, with the fast development of network technology, communication technology, Internet of Things (IoT) technology, etc., the smart home enters the outbreak period of development. Thus, the concept of smart home has changed a lot than before.

Nowadays, almost all the typical home appliances (TV, light, air conditioner, etc.) can be controlled in the smart home as shown in Fig 2.1.

- For the smart TV, it can connect to the Internet to access or download music and video by some applications. It can also be controlled by voice or gesture recognition.

- For the smart light system, users can control it not only by switch, but also by some applications in the smart phone. The adjustment of color and light intensity can also be achieved with smart light bulbs.

- For the smart thermostats, like energy efficient thermal comfort control (EETCC) system [8], come with integrated ECHONET [9], can reduce power consumption as well as satisfy the thermal comfort level of residents by using air-conditioner, window, and curtain. The benefits of EETCC system is that it uses the natural resources like window and curtain to adjust the thermal comfort.

- For the smart lock, it can detect the location of resident smartly and unlock automatically if resident is nearby. The resident can allow or deny the access of visitors too.

- For the smart home security system, it uses web cameras in order to make the home situation can be monitored when the resident is not at home. By the image identification technology and artificial intelligence technology, residents, visitors, pets and burglars can be easily identified, and resident can also receive notification in some cases.

- For the smart kitchen system, it can control appliances like refrigerator, electric cooker, coffee-maker, dishwasher, etc. automatically. Smart refrigerators can record expiration dates of the foods and keep tracking, and residents will be told if some of them have expired. Besides, if the amount of your favourite food is not enough, maybe the eggs, smart refrigerators can buy it automatically through the Internet. Also, it can provide a menu about how to cook perfect dishes according to the food inside.

With the development of the society, the application fields of smart homes will become more and more extensive. The concept of smart home is changing at any time.

2.3 Components of Smart Home

For smart home, the components must be employed includes the following elements: intelligent control, home automation and internal network [10] as shown in Fig 2.2. The intelligent control is provided by a control system, comprised of two types of elements, i.e., sensors and control agent. Sensors is used to monitor, report the status of the home situation and control the home appliance [11].

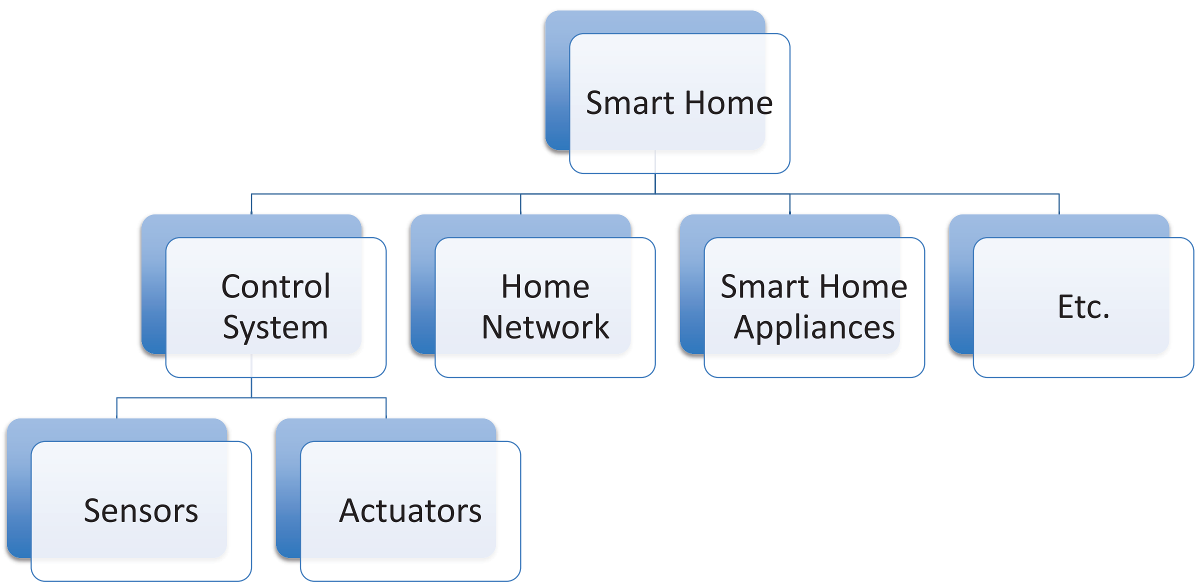

Figure 2.2: Components of smart home

The control system is the core of smart home which can control all kinds of smart devices according to the whole information from inside or outside the house. And then the control system can provide a smarter choice for different types of lifestyles, for instance it can adjust the air temperature by controlling the air conditioner or adjust the light according to the environment indoor and outdoor. Home automation is the actuator that can work according to the commands issued by the control system to achieve the desired goals like smart TV, smart light mentioned in last section. Home network can be divided into wired network and wireless network. Wired network, such as TV cable, Wireless LAN cable, etc. can be simply configured with low cost. But it cannot be extended easily and may be interfered easily which is considered to be unreliable. Wireless network does not need any wires to operate. The typical techniques such as Wi-Fi, ZigBee are generally used because of its low cost.

For this research, the main focus is on the heating, ventilation and air-conditioning system (HVAC) system and V2H system. HVAC system can change the temperature, humidity, etc. to improve the comfort of residents. V2H system is becoming more and more important because of the wildly use of EV.

- Heating, Ventilation and Air-Conditioning System

  The HVAC system as shown in Fig 2.3 is an important part of every smart home. This system works much more than programmable thermostats and timer controls [12]. Resident can feel comfortable and reduce the cost by using a control system which can keep the home well-insulated or ventilated, such as EETCC system [8].

- Electric Vehicle to Home System

  The V2H system must include EV, smart devices like HEMS and smart meter(SM), RES system, energy storage system (ESS), controllable loads and some communication systems.

  - Smart Devices

    Nowadays, more and more people are giving attention to the smart home which can monitor electricity price and power consumption in real time and take actions to reduce costs. Thus, the focus on managing demand response (DR) is become more important than before. The key strategy of it is the interaction between smart home and users. In this context, HEMS and smart metering infrastructure, such as SM, play an essential role in the effective implementation of DR strategy and V2H system for residential areas.

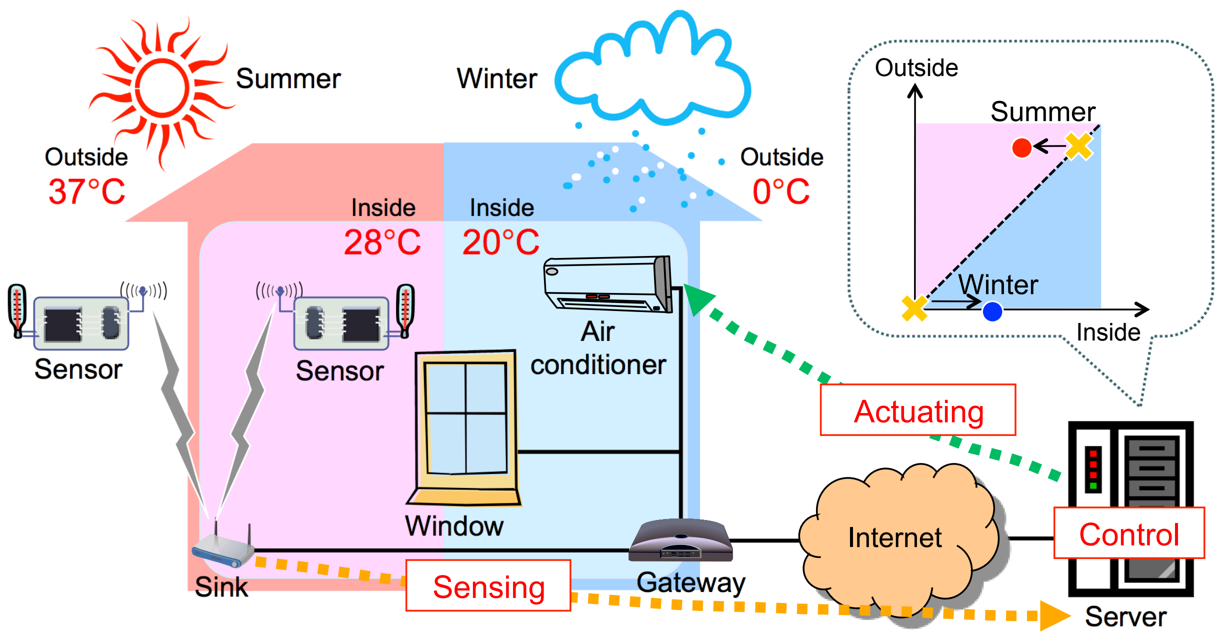

Figure 2.3: Heating, ventilation and air-conditioning system

– Home Energy Management System

The HEMS must support the implementation of demand response on the residential side, the access of renewable energy sources or new types of loads such as wind power generation, PV and EV to the power grid. EVs need to be connected to the grid in an orderly manner under the control of the HEMS to eliminate the hazards caused by the large number of EVs. And due to the intermittent and random nature of wind and PV, it is necessary to use HEMS to improve the power quality of wind power and PV generation, maintain system stability and improve its utilization. Wind power and PV are mainly supplied to users themselves, and excess power is sold to the power grid. And the HEMS must have both energy exchange and information exchange with the power grid. To achieve these functions, the HEMS has five main modules.

(1) User settings module. The user sets parameters of the devices in the home environment through the man-machine interface, such as the limits of the indoor environment temperature, the start time of the DW, the charging com-

pletion time of the EV and so on. The priority of different can be set too. The user can complete all settings related to the system through this module.

(2) Detection module. The detection module is used to the environmental detection, device detection and user behaviour detection. Environmental detection includes indoor temperature, humidity, illumination and other factors. Device detection includes the use of electrical loads, energy storage systems, distributed powers, such as the status of EV, the charging power, battery state of charge and so on. User behaviour detection includes user physical location detection and identification of user behaviour.

(3) Prediction module. Wind power and PV generation have the unstable characteristics. Using predictive algorithms to predict their power output is beneficial to improve their utilization. If users use real-time electricity prices, it needs to forecast electricity prices too. In addition, they can predict the load in the home environment. These predictions are used to optimize the scheduling to improve system performance.

(4) Scheduling module. This module is the core of the HEMS. It can schedule the loads and energy storage in the home environment based on user settings, working status of appliances, environmental information, personnel activity information, electricity price information, and renewable energy output prediction to achieve an optimal target set by the user, such as minimizing the electricity cost.

(5) Equipment monitoring module. This module controls the operation of the power load and the energy storage system according to the calculation result of the optimized scheduling module, monitors the working state of the equipment in real time, and reflects the working state of the equipment and the current power consumption state to the user through the human-machine interface in real time. Unlike traditional HEMS, the new HEMS in a smart micro-grid environment can optimize and manage the energy used in both single home environment and multiple home environment. Therefore, the new HEMS in

a smart micro-grid environment requires the supports of home area network, neighbourhood area network and wide area network.

Each HEMS contains a SM which is the interface between the home network and the external network for information exchange. Many SMs in the same area form a cell network, data from each SM is aggregated in the cell network data aggregation center, and then sent to the power company through the wide area network for functions such as energy metering and load forecasting.

Demand response issued by the power company control commands, electricity prices and other information are transmitted along the opposite path.

– Smart Meter

  A SM can collect electricity price, power consumption and some other information. Then, it can provide data to the users. This advanced metering infrastructure (AMI) differs from traditional automatic meter reading (AMR) because it allows two-way communication [13]. But, the success of demand control is based on a complete automation of home appliances.

– Renewable Energy Source System

  Most of smart homes have PV system, and some of smart homes also have wind turbine system. But sun and wind are unstable phenomenon that cannot be fully forecasted. In general, Markov chain is used in the forecast of sun and wind based on historical data.

– Energy Storage System

  For the activities of EVs, in general, users spend every day about 75 minutes on average driving, covering an average distance of 40 km per person [14], [15]. With this data, an EV with 100 km of autonomy would be the replacement for about 85% of users, assuming daily load [16]. According to [2], most people use their vehicle from 8:00 to 9:00 a.m. and from 4:00 to 5:00 p.m. This way, most vehicles are at home from 8:00 p.m. to 7:00 a.m. and are available during 11 hours, to be used as a storage system.

The home energy storage system must consider the output of PV and wind power, the demand of users, for example, Tesla Motors has already presented a battery in the market, for residential use, in support of renewable generation systems. This will allow the supply of households with less dependence on the grid and the integration of solar and wind energy [17].

2.4 Electric Vehicle

EV is a vehicle that is driven by a vehicle power source and drives the wheels with one or more electric motors. EVs first came into existence in the mid-19th century, when electricity was among the preferred methods for motor vehicle propulsion, providing a level of comfort and ease of operation that could not be achieved by the gasoline cars of the time. In the 21st century, EVs saw a resurgence due to technological developments, and an increased focus on renewable energy. There are three main kinds of EVs: hybrid electric vehicle (HEV), battery electric vehicle (BEV) and fuel cell electric vehicle (FCEV), any of them has its characteristics which can meet different demands of different users. So, it will be used widely in the near future.

- Hybrid Electric Vehicle

  The vehicle drive system of HEV is composed of two or more single drive systems that can operate at the same time. Depending on the actual vehicle travel state, the driving power of the vehicle is provided by a single drive system separately or jointly. Hybrid power unit not only has the advantages of the engine such as the long engine working time and good power, but also can benefit from the electric motor which is pollution-free and low-noise. When an engine is combined with an electric motor, both of the advantages can be achieved and then, the thermal efficiency of the car can be increased by more than 10%, the degree of exhaust emissions can be improved by more than 30%. But the disadvantages of HEV is its complex structure and dependence on fuel.

- Battery Electric Vehicle

BEV is a car that is powered by the rechargeable battery entirely, such as lead-acid battery, nickel-cadmium battery, nickel-metal hydride battery, or lithium-ion battery. The advantages of BEV is zero release, non-pollution and simple structure but it is too expensive and endurance mileage is limited.

- Fuel Cell Electric Vehicle

  FCEV is a vehicle powered by the electric generated by a vehicle fuel cell device which's fuel is the high-hydrogen reformed gas obtained by reforming high-purity hydrogen or a hydrogen-containing fuel. The key to FCEV is the fuel cell because compared to conventional electric vehicles, the difference in power is that the power used by the electric vehicle comes from the battery which is charged by the grid, but the power used by the FCEV comes from the on-board fuel cell device. The endurance mileage of FCEV is long than BEV, but the cost, the conservation of hydrogen are still problems need to be solved.

In the US, it is predicted that by 2020 25% and by 2040 two thirds of light-duty vehicles ought to be EVs. Further, it is expected that current research outcomes on high power lithium-ion micro battery technology will accelerate the replacement of internal combustion cars by the EVs [18].

There are two main places where the battery of EVs can be charged: at public parking, or at home. And there are two main ways of charging: fast charging and ordinary charging. However, human EV activities will have a significant impact on the power distribution network (smart grid) if charging and discharging of EVs are not controlled appropriately.

For example, the distribution systems are typically designed based on the typical load. But fast charging of EVs is required like ordinary cars need to be refueled during a long drive on the express-way. Ordinary charging is required when the users back to home. So, when EVs are deployed in the distribution system, the patterns of electric power demand on the grid system will change due to added load resulting from EV charging. The extent to which the deployments of EVs affect the distribution grid depends on their charging characteristics which include charging power level and charging time. Fast charging of EVs involve delivering required energy in a short time interval, usually in a range of minutes which results in high charging power. The high charging power demand from a number of plug-in EVs (PEVs) can produce pulsating load in the system which leads to voltage flicker in the distribution grid and affect transformer loading. Ordinary charging of EVs requires continuous energy which may lead to the increasing of peak load and home electricity cost because of the centralized charging of EVs in a community.

So, to solve these problems, it is necessary to analyze the residents' activities, battery storage, charging power level, charging time and so on.

Chapter 3

Model of the System

In this chapter, I introduce the experiment environment, model of modules in V2H system, schedules of household members, based on these, I will propose the joint optimization scheme for smart homes in next chapter.

3.1 Experiment Environment

- iHouse

Figure 3.1: iHouse

iHouse as shouw in Fig 3.1 is an advanced experimental house of smart home. This two-story house (Fig 3.2) was built in Nomi city, Ishikawa prefecture Japan. There are more than 300 sensors, appliances and electronic devices in iHouse and they are connected by ECHONET Lite version 1.1 and ECHONET version 3.6. In this research, the raw data are obtained from iHouse.

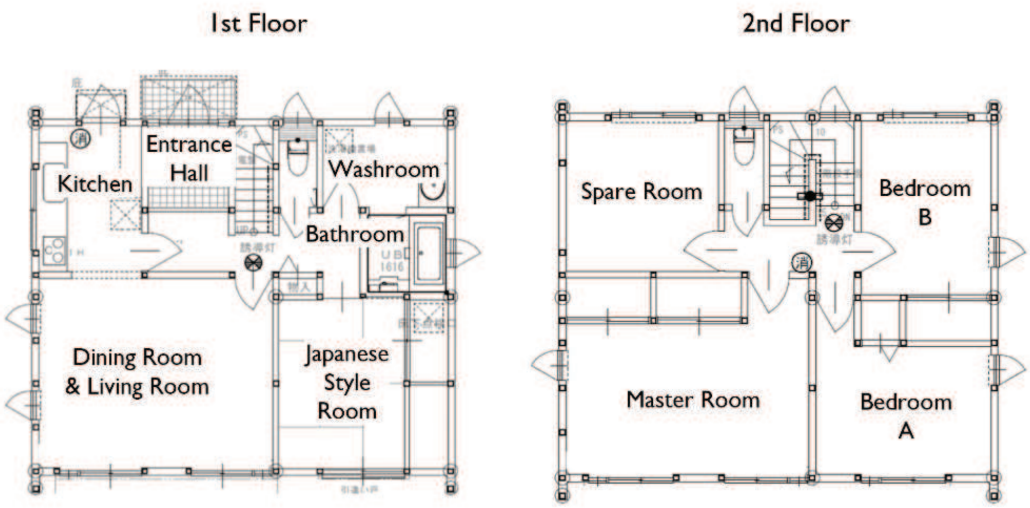

Figure 3.2: Layout plan of iHouse

- Smart Community Simulator

  The smart community simulator (see Fig 3.3) is a large simulation software with an objective of improving the quality of life (QoL) of smart community with the knowledge of energy saving, water saving, transportation, health, etc. In this research, the smart community simulator is used to simulate the energy demand and supply of smart home. The electric and heat consumptions are simulated based on the residents' activities and the physical conditions of iHouse environment. In this research, the smart home model (see Fig3.4) extends the smart home model of smart community simulator.

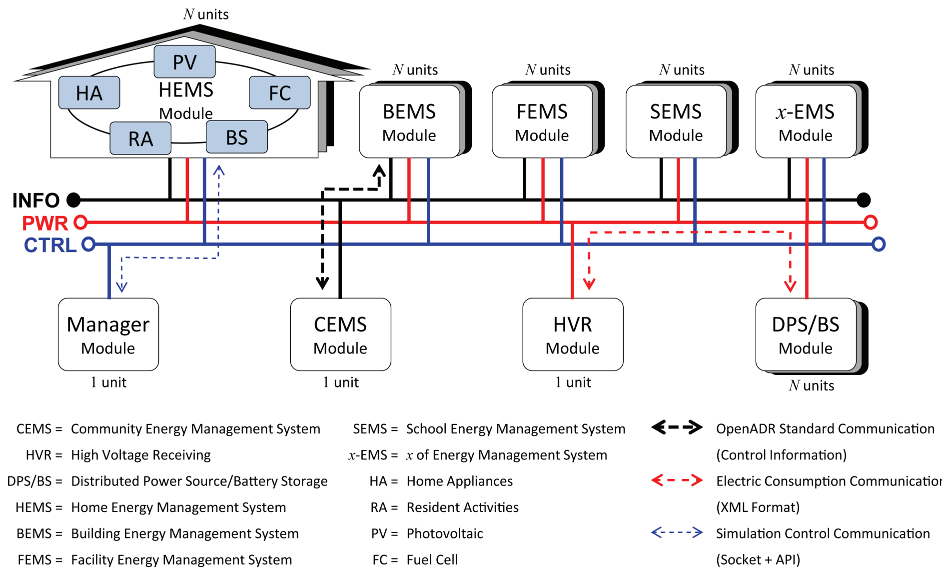

Figure 3.3: Smart community simulator

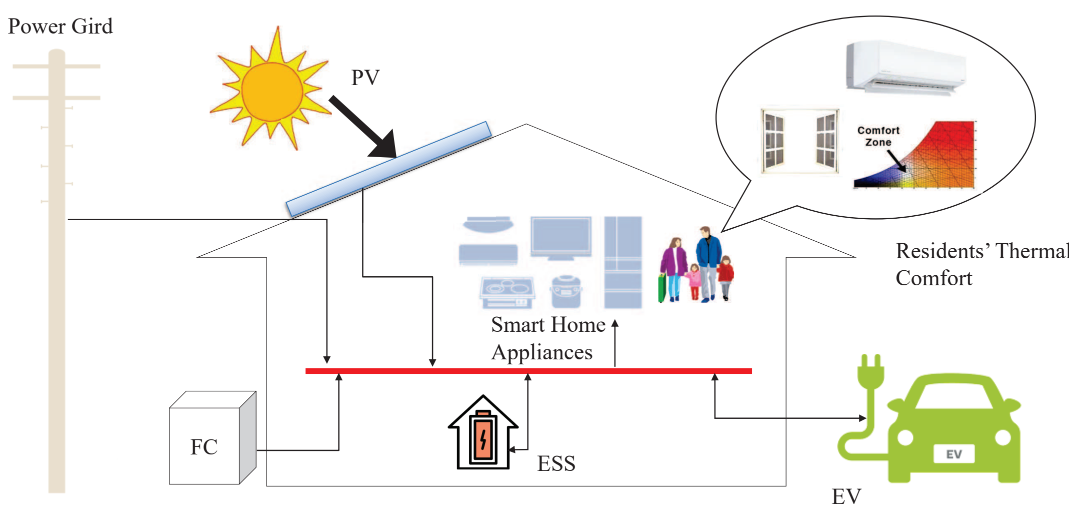

Figure 3.4: Smart home model of smart community simulator

3.2 Model of Renewable Energy Source

A PV and a FC energy system are used in iHouse, so in this section, only PV and FC are discussed.

- Solar Photovoltaic

  PV can convert the solar radiation into the electricity. The application fields of PV power generation are quite extensive. Solar water heaters and solar greenhouses have been used for a long time in our daily life. At the same time, PV power generation, as an important distributed energy source, plays an important role in the field of new energy generation. As PV power generation technology becomes more and more mature, it will surely enter more and more homes of ordinary users as an important energy source in the home micro-grid. The PV panel can receive three different kinds of radiation (Fig 3.5), direct radiation, reflected radiation, and diffuse radiation. Direct radiation is the sunlight to the panel directly. Reflected radiation is a reflected sunlight by the ground. And diffuse radiation is a scattered sunlight by the cloud.Sandia National Laboratories [19] proposes that the power generated from PV in the unit of Watt is given by

$$P_{PV} = \varepsilon R A_{PV} \mu_{soil} \left(1 - \varepsilon_{thermal} \left(\frac{T_{panel} - 25}{100}\right)\right) \tag{3.1}$$

  where ε is the efficiency of PV panel, R is the solar irradiance (unit is Wm^{-2}), A_{PV} is the area of PV panel (unit is m^2), μ_{soil} is the soiling coefficient, $\varepsilon_{thermal}$ is the thermal efficiency of PV panel ($°C^{-1}$) and T_{panel} is the temperature of PV panel. The temperature of PV panel that is affected by surrounding objects and the reflected radiation can lead to high fluctuation on the generated power from PV. Therefore, it is necessary to use the filter.

  In this reasearch, the energy generated by PV is collected from the history data of iHouse. The parameters of PV are listed in Table 3.1.

- Fuel Cell

  FC can convert the chemical energy into the electricity and heat. Proton exchange membrane fuel cell (PEMFC) is the most common type of fuel cell. The basic structure of PEMFC is two electrodes (anode and cathode) that are separated by a solid membrane as shown in Fig 3.6. A hydrogen gas is fed continuously to the

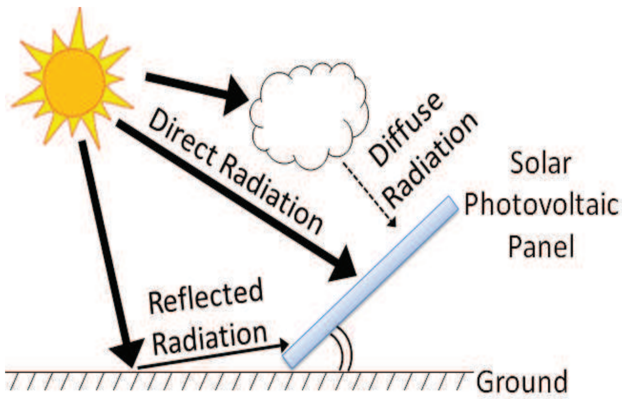

Figure 3.5: Solar radiation towards PV panel

Model	HIT-N225A01
PV panel size	1.58m × 0.79m
Panel type	Monocrystalline
Efficiency of PV panel	0.202
Maximum voltage	43.4 Volts
Open circuit voltage	53.0 Volts

Table 3.1: Parameters of PV

anode and air is fed to the cathode. A chemical reaction will happen, and the electricity and heat are produced. The energy generated from FC is given by

$$E_{FC} = M_{gas} LHV \tag{3.2}$$

where M_{gas} is the mass of hydrogen gas (unit is kg) and LHV is the low heat value of hydrogen gas (unit is kWh/kg).

In this research, the basic FC model is shown in Fig 3.7, the energy generated by FC is calculated based on JIS C8851 standard [20] (see Fig3.8) and the simulation of residents' activities [21].

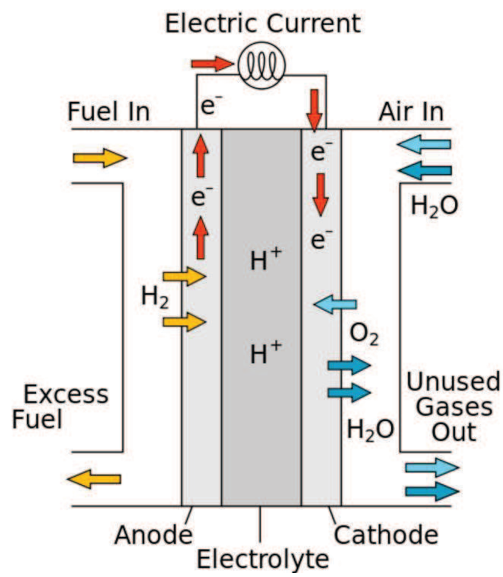

Figure 3.6: PEMFC simplified diagram

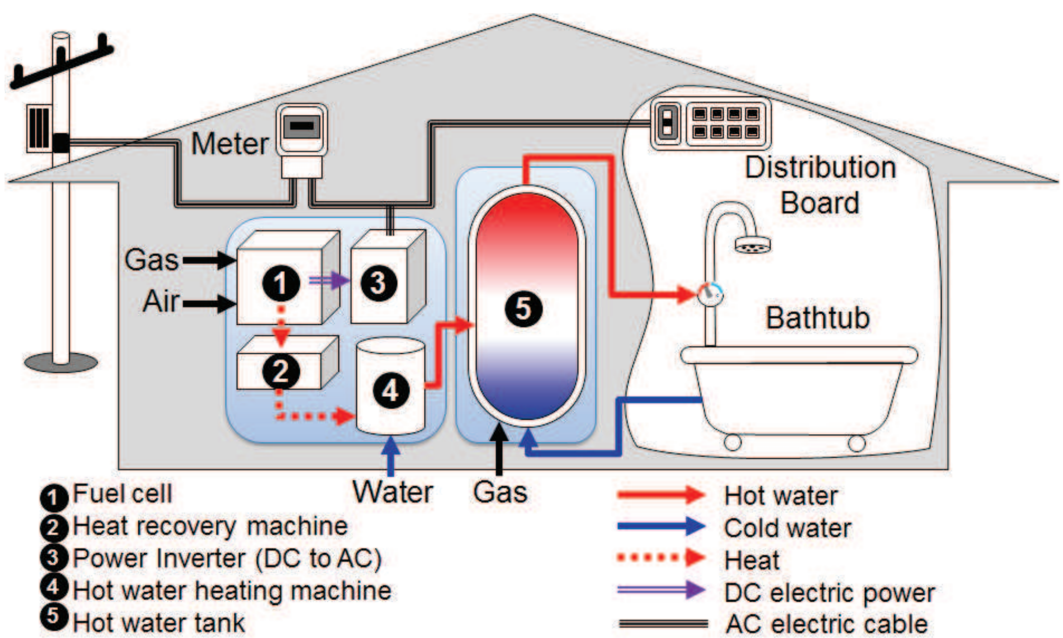

Figure 3.7: Basic FC model

The parameters of FC are listed in table 3.2.

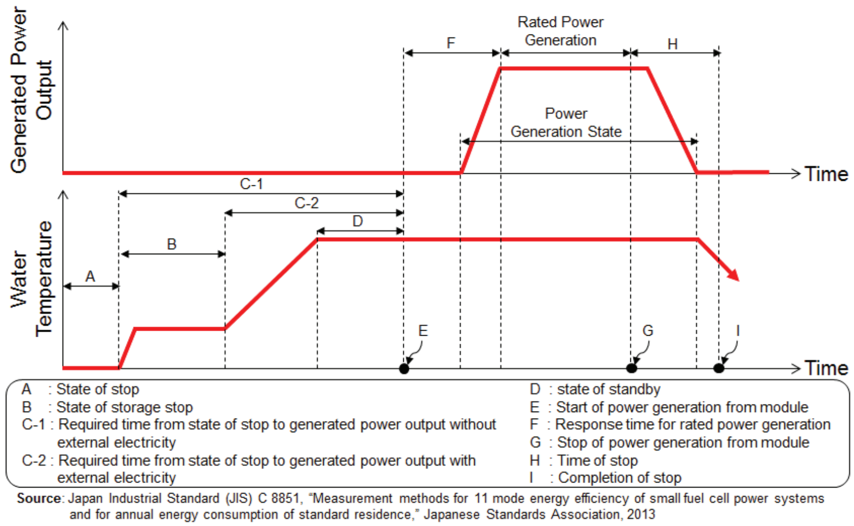

Figure 3.8: JIS C 8851 standard on operation process diagram of fuel cell power generation unit

Electrical efficiency	0.39
Exhaust heat recovery efficiency	0.56
Rated power	7kW
Average fuel pressure	2.5kPa
Average atmospheric pressure	101.3kPa
Average fuel temperature	25°C
LHV	33.2kWh/m^3
Size of hot water tank	200 liters
Water density	1000kg/m^3
Heat transfer coefficient	0.1kW/m^2K
Surface area of hot water tank	4.8488 m^2
Storage mode temperature	35°C
Desired temperature of hot water tank	20°C

Table 3.2: Parameters of FC

3.3 Simulation of Residents' Activities

In the simulation, father, mother ,daughter, and son are assumed in the iHouse, based on [22]. The daily electric price (see Fig3.9) is used to calculate the total electricity cost per day.

- Schedule of Household Member

00:00 06:30	Sleep
06:30 06:45	Personal care
06:45 07:30	TV & Breakfast
07:30 19:00	Work
19:00 20:00	TV & Dinner
20:00 22:00	Leisure
22:00 22:30	Bathing
22:30 23:30	Leisure
22:00 22:30	Sleep

Table 3.3: Schedule of father

00:00 06:00	Sleep
06:00 06:15	Personal care
06:15 07:00	Cooking
07:00 08:00	TV & Breakfast
08:00 10:00	Housework
10:00 11:30	Leisure
11:30 12:00	Cooking
12:00 12:30	TV & Lunch
12:30 13:30	Housework
13:30 14:30	Leisure
14:30 17:00	Shopping
17:00 18:15	Housework & Leisure
18:15 19:00	Cooking
19:00 20:00	TV & Dinner
20:00 21:00	Housework
21:00 22:30	Leisure
22:30 23:00	Bathing
23:00 23:30	Leisure
23:30 00:00	Sleep

Table 3.4: Schedule of mother

00:00 07:00	Sleep
07:00 07:30	Personal care
07:30 08:00	TV & Breakfast
08:00 18:00	School
18:00 19:00	Study & Leisure
19:00 20:30	TV & Dinner
20:30 21:00	Bathing
21:00 23:30	Study & Leisure
23:30 00:00	Sleep

Table 3.5: Schedule of daughter

00:00 06:45	Sleep
06:45 07:00	Personal care
07:00 08:00	TV & Breakfast
08:00 17:30	School
17:30 19:00	Study & Leisure
19:00 20:00	TV & Dinner
20:00 20:30	Bathing
20:30 23:00	Study & Leisure
23:00 00:00	Sleep

Table 3.6: Schedule of son

Fig 3.10 shows the location of residents' activities.

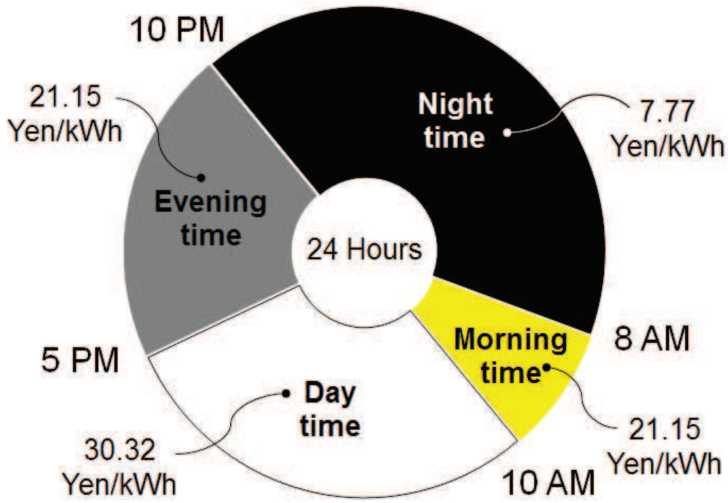

Figure 3.9: Daily electric price

- Daily Electric Price

  The daily electric price is shown in Fig 3.9. The source of daily electric price comes from Tokyo Electric Power Company.

<table>
<tr><th>Time</th><th colspan="2">Father</th><th colspan="2">Mother</th><th colspan="2">Child1(college student) 20 years old</th><th colspan="2">Child2(high school student) 16 years old</th></tr>
<tr><th></th><th>Activity</th><th>Location</th><th>Activity</th><th>Location</th><th>Activity</th><th>Location</th><th>Activity</th><th>Location</th></tr>
<tr><td>0:00</td><td rowspan="26">Sleep</td><td rowspan="26">Master bedroom</td><td rowspan="24">Sleep</td><td rowspan="24">Master bedroom</td><td rowspan="28">Sleep</td><td rowspan="28">Bedroom1</td><td rowspan="27">Sleep</td><td rowspan="27">Bedroom2</td></tr>
<tr><td>0:15</td></tr>
<tr><td>0:30</td></tr>
<tr><td>0:45</td></tr>
<tr><td>1:00</td></tr>
<tr><td>1:15</td></tr>
<tr><td>1:30</td></tr>
<tr><td>1:45</td></tr>
<tr><td>2:00</td></tr>
<tr><td>2:15</td></tr>
<tr><td>2:30</td></tr>
<tr><td>2:45</td></tr>
<tr><td>3:00</td></tr>
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<tr><td>3:30</td></tr>
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<tr><td>4:00</td></tr>
<tr><td>4:15</td></tr>
<tr><td>4:30</td></tr>
<tr><td>4:45</td></tr>
<tr><td>5:00</td></tr>
<tr><td>5:15</td></tr>
<tr><td>5:30</td></tr>
<tr><td>5:45</td></tr>
<tr><td>6:00</td><td>Personal Care</td><td>Restroom</td></tr>
<tr><td>6:15</td><td rowspan="3">Cooking</td><td rowspan="3">Kitchen</td></tr>
<tr><td>6:30</td><td>Personal Care</td><td>Restroom</td></tr>
<tr><td>6:45</td><td rowspan="3">TV and Breakfast</td><td rowspan="3">Living room</td><td>Personal Care</td><td>Restroom</td></tr>
<tr><td>7:00</td><td rowspan="4">TV and Breakfast</td><td rowspan="4">Living room</td><td rowspan="2">Personal Care</td><td rowspan="2">Restroom</td><td rowspan="4">TV and Breakfast</td><td rowspan="4">Living room</td></tr>
<tr><td>7:15</td></tr>
<tr><td>7:30</td><td colspan="2" rowspan="46">Work</td><td rowspan="2">TV and Breakfast</td><td rowspan="2">Living room</td></tr>
<tr><td>7:45</td></tr>
<tr><td>8:00</td><td rowspan="8">Housework</td><td rowspan="8">Moving around</td><td colspan="2" rowspan="40">School</td><td colspan="2" rowspan="38">School</td></tr>
<tr><td>8:15</td></tr>
<tr><td>8:30</td></tr>
<tr><td>8:45</td></tr>
<tr><td>9:00</td></tr>
<tr><td>9:15</td></tr>
<tr><td>9:30</td></tr>
<tr><td>9:45</td></tr>
<tr><td>10:00</td><td rowspan="6">Leisure</td><td rowspan="6">Living room</td></tr>
<tr><td>10:15</td></tr>
<tr><td>10:30</td></tr>
<tr><td>10:45</td></tr>
<tr><td>11:00</td></tr>
<tr><td>11:15</td></tr>
<tr><td>11:30</td><td rowspan="2">Cooking</td><td rowspan="2">Kitchen</td></tr>
<tr><td>11:45</td></tr>
<tr><td>12:00</td><td rowspan="2">Lunch</td><td rowspan="2">Living room</td></tr>
<tr><td>12:15</td></tr>
<tr><td>12:30</td><td rowspan="4">Housework</td><td rowspan="4">Moving around</td></tr>
<tr><td>12:45</td></tr>
<tr><td>13:00</td></tr>
<tr><td>13:15</td></tr>
<tr><td>13:30</td><td rowspan="4">Leisure</td><td rowspan="4">Living room</td></tr>
<tr><td>13:45</td></tr>
<tr><td>14:00</td></tr>
<tr><td>14:15</td></tr>
<tr><td>14:30</td><td colspan="2" rowspan="10">Shopping</td></tr>
<tr><td>14:45</td></tr>
<tr><td>15:00</td></tr>
<tr><td>15:15</td></tr>
<tr><td>15:30</td></tr>
<tr><td>15:45</td></tr>
<tr><td>16:00</td></tr>
<tr><td>16:15</td></tr>
<tr><td>16:30</td></tr>
<tr><td>16:45</td></tr>
<tr><td>17:00</td><td rowspan="5">Housework and Leisure</td><td rowspan="5">Moving around</td></tr>
<tr><td>17:15</td></tr>
<tr><td>17:30</td><td rowspan="6">Study and Leisure</td><td rowspan="6">Bedroom2</td></tr>
<tr><td>17:45</td></tr>
<tr><td>18:00</td><td rowspan="4">Study and Leisure</td><td rowspan="4">Bedroom1</td></tr>
<tr><td>18:15</td><td rowspan="3">Cooking</td><td rowspan="3">Kitchen</td></tr>
<tr><td>18:30</td></tr>
<tr><td>18:45</td></tr>
<tr><td>19:00</td><td rowspan="4">TV and Dinner</td><td rowspan="4">Living room</td><td rowspan="4">TV and Dinner</td><td rowspan="4">Living room</td><td rowspan="6">TV and Dinner</td><td rowspan="6">Living room</td><td rowspan="4">TV and Dinner</td><td rowspan="4">Living room</td></tr>
<tr><td>19:15</td></tr>
<tr><td>19:30</td></tr>
<tr><td>19:45</td></tr>
<tr><td>20:00</td><td rowspan="8">Leisure</td><td rowspan="8">Living room</td><td rowspan="4">Housework</td><td rowspan="4">Moving around</td><td rowspan="2">Bathing</td><td rowspan="2">Bathroom</td></tr>
<tr><td>20:15</td></tr>
<tr><td>20:30</td><td rowspan="2">Bathing</td><td rowspan="2">Bathroom</td><td rowspan="10">Study and Leisure</td><td rowspan="10">Living room</td></tr>
<tr><td>20:45</td></tr>
<tr><td>21:00</td><td rowspan="6">Leisure</td><td rowspan="6">Living room</td><td rowspan="10">Study and Leisure</td><td rowspan="10">Living room</td></tr>
<tr><td>21:15</td></tr>
<tr><td>21:30</td></tr>
<tr><td>21:45</td></tr>
<tr><td>22:00</td><td rowspan="2">Bathing</td><td rowspan="2">Bathroom</td></tr>
<tr><td>22:15</td></tr>
<tr><td>22:30</td><td rowspan="4">Leisure</td><td rowspan="4">Living room</td><td rowspan="2">Bathing</td><td rowspan="2">Bathroom</td></tr>
<tr><td>22:45</td></tr>
<tr><td>23:00</td><td rowspan="2">Leisure</td><td rowspan="2">Living room</td><td rowspan="4">Sleep</td><td rowspan="4">Bedroom2</td></tr>
<tr><td>23:15</td></tr>
<tr><td>23:30</td><td rowspan="2">Sleep</td><td rowspan="2">Master bedroom</td><td rowspan="2">Sleep</td><td rowspan="2">Master bedroom</td><td rowspan="2">Sleep</td><td rowspan="2">Bedroom1</td></tr>
<tr><td>23:45</td></tr>
</table>

Source: NHK Broadcasting Culture Research Institute, "Time habits of Japanese in 2005: A NHK survey regarding the use of time in the daily life of Japanese citizens," Japan Broadcasting Publishers Association, 2006

Figure 3.10: Location of residents' activities.

3.4 Model of Electric Vehicle

During the development of EV, the energy storage elements have always been the focus of research. Rechargeable battery such as lead-acid battery, nickel-cadmium battery, nickel-metal hydride battery, or lithium-ion battery and super-capacitor are commonly used in EV as energy storage elements. At present, lithium-ion battery with its high energy density, stability of voltage, environment-friendly, long lasting, etc. has been widely used.

TESLA Model S, BMW i3 and NISSAN Leaf are common EV in our daily life, the characteristics of them are listed in table 3.7. In this research, NISSAN Leaf is used.

Model of EV	Capacity of Battery	Maximum Range
TESLA Model S	60kWh	600km
BMW i3	30kWh	250km
NISSAN Leaf	40kWh	400km

Table 3.7: Characteristics of EV

It is necessary to know the state of charge (SOC) of EV in order to decide the charging, discharging time. The SOC is calculated by

$$SOC = \frac{RE}{Cap} \tag{3.3}$$

where RE is remaining energy of the battery; Cap is the capacity of the battery.

The lithium-ion battery model in matlab/simulink is used here to analyze the progress of charging and discharging. The capacity of ESS is 10kWh, the power of ESS is 4kW during charging and discharging, the power of EV is 6kW during charging and discharging [23].

The progress of charging needs AC/DC converter as shown in Fig 3.11.

The progress of discharging needs DC/DC converter as shown in Fig 3.12.

The change of SOC of EV and ESS during charging of EV are shown in Fig 3.13 and Fig 3.14 respectively.

The change of SOD of EV and ESS during discharging of EV are shown in Fig 3.15 and Fig 3.16 respectively.

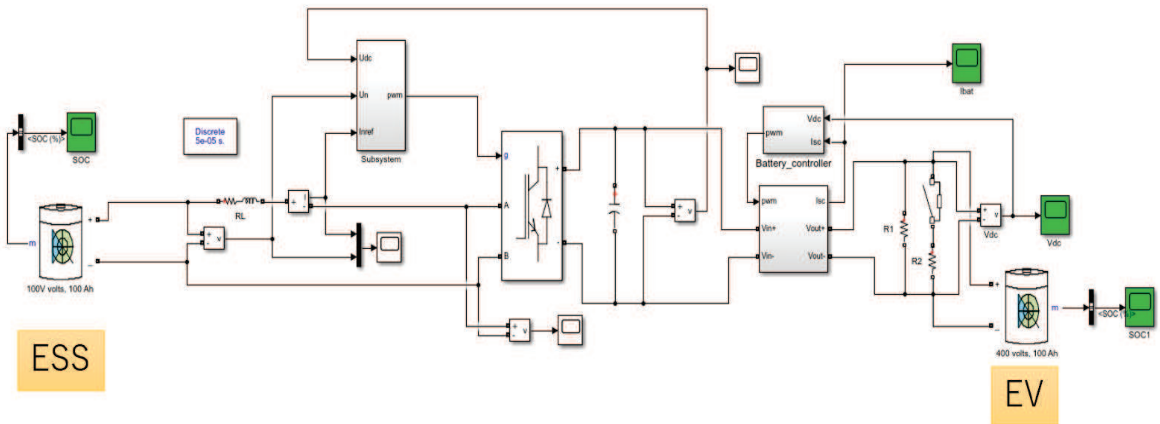

Figure 3.11: Circuitry of AC/DC

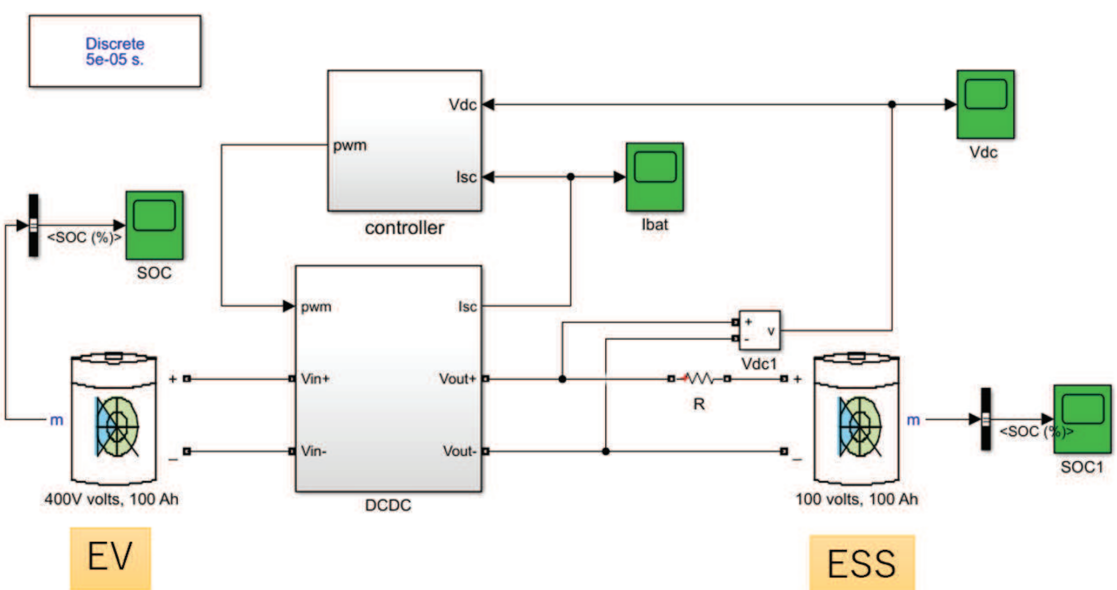

Figure 3.12: Circuitry of DC/DC

In addition, the relationship between average daily travel distance and probability is expressed as follow and in Fig 3.17 :

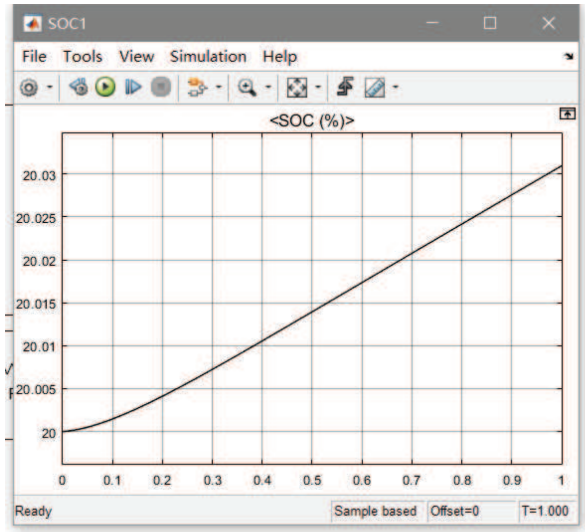

Figure 3.13: Change of EV SOC

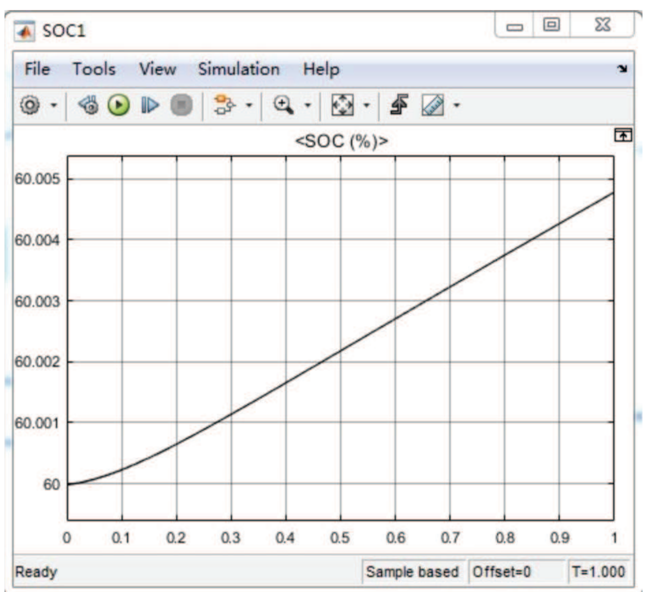

Figure 3.14: Change of ESS SOC

$$f_{L_d}(x) = \frac{1}{x\sigma_D\sqrt{2\Pi}} exp[-\frac{(lnx - \mu_D)^2}{2\sigma_D^2}] \tag{3.4}$$

where $f_{L_d}(x)$ is probability, μ_D is expected value of travel distance, σ_D is standard

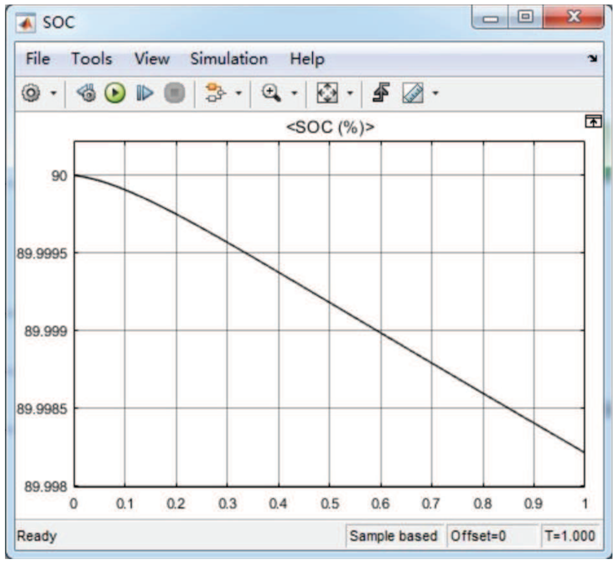

Figure 3.15: Change of EV SOD

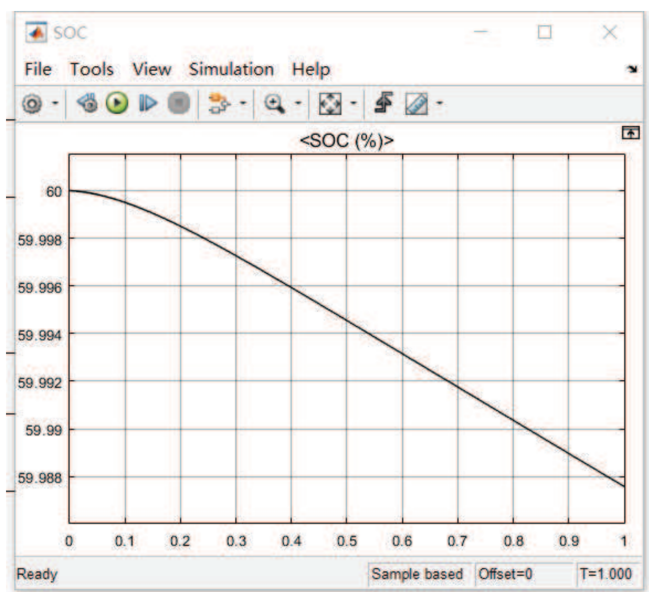

Figure 3.16: Change of ESS SOD

deviation of travel distance, x is travel distance. It is assumed to be 54km under the typical driving pattern $\mu_D = 3.2$, $\sigma_D = 0.88$ [24], [25], [26], [27]. And the change of SOC of EV a day is shown in Fig 3.18based on these data if discharging is not considered.

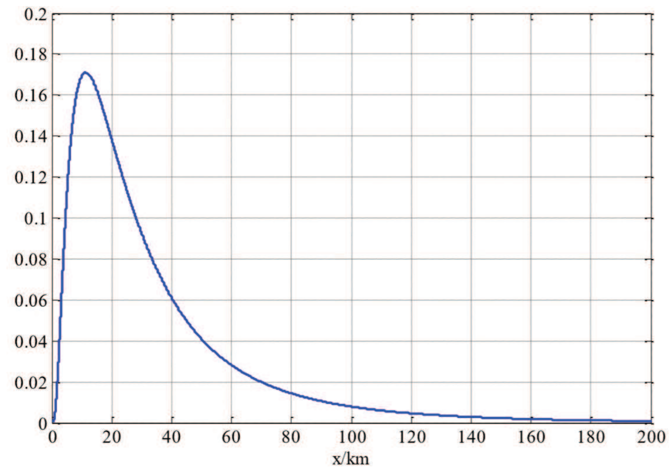

Figure 3.17: Relationship between probability and average daily travel distance

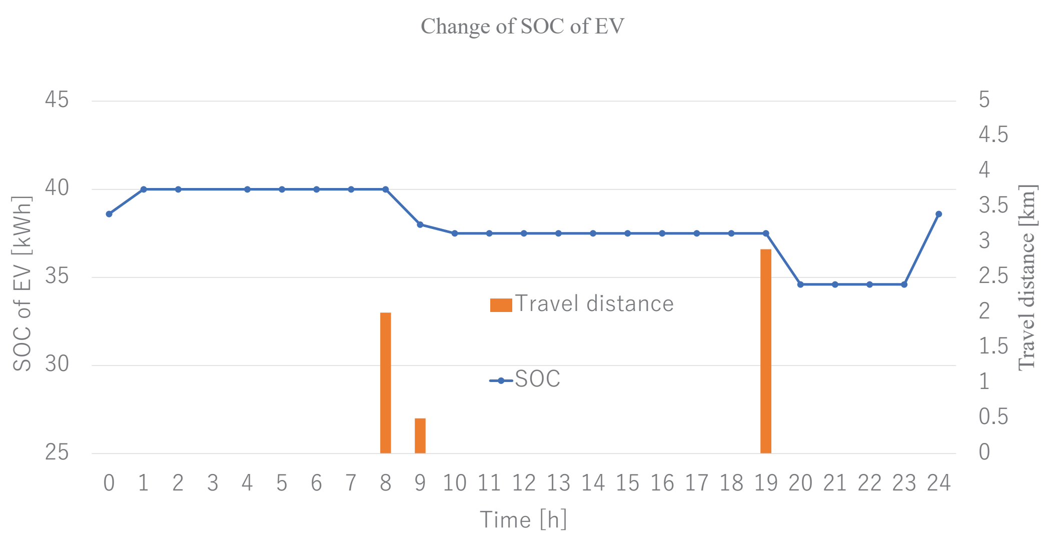

Figure 3.18: The change of SOC of EV a day

3.5 Model of Home Appliances

There are four main types of appliances in typical house:

Type 1, appliances that can be delayed for a certain time such as dishwasher (DW), cloth washer (WA), cloth dryer (DR), and swimming pool pump (PP).

Type 2, appliances whose operation schedule depends on its charging characteristics such as EV.

Type 3, appliances that can be adjusted with the change in the temperature set point such as water heater (WH) and air-conditioner (AC).

Type 4, appliances that have strict scheduling requirement such as refrigerator, computer, home entertainment systems, lighting systems, security systems.

Scheduling the operation of Type 1, 2 under certain conditions does not affect the residents' comfort but can change the cost. Scheduling the operation of Type 3 can seriously affect user satisfaction. Optimizing the operation of schedulable loads is an important way to achieve the demand response of the residents.

Thermal comfort is described as the state of the mind that expresses satisfaction with its thermal surrounding [8]. The PMV model is the most recognized thermal comfort model which is affected by six factors. They are metabolic rate, clothing level, air temperature, mean radiant temperature, air speed and humidity. In this research, the air temperature is used to reflect the residents' comfort preference.

The daily power consumption is based on the home appliances of iHouse and [28], [29].

Chapter 4

System Design

In this Chapter, the joint optimization scheme for smart homes is proposed based on the different objective functions and constraint conditions for four seasons. The first section introduces the objective functions and constrain conditions. The second section is about the schemes for four seasons.

4.1 Objective Function and Constrain Condition

- Objective Function

  The objective of this research is to propose a joint optimization scheme to determine the best charging and discharging time in order to minimize the cost while considering the residents' thermal comfort. The objective function is expressed as follows:

$$C = \sum_{t=0}^{24} (P_{grid}(t) \cdot price(t)) \tag{4.1}$$

P,T and price: *minimize C*

subject to $T^{season}_{lowerbound} < T^{season}_{room} < T^{season}_{upperbound}$

$$P_{ESS} \text{ and } P_{EV} > 0$$

where C is total cost in a day (yen), C is temperature ($^{\circ}C$), P is power (Watt), season can be winter, spring, summer, autumn

- Constrain Condition

  The optimization scheme is subject to the following constrains:

  - Constrain of Energy Balance

$$P_{grid}(t) + P_{PV}(t) + P_{FC}(t) + P_{ESS}^{discharging}(t) = P_{HVAC}(t) + P_{EV}^{charging}(t) + P_{load}(t) \tag{4.2}$$

$$P_{grid}(t) + P_{PV}(t) + P_{FC}(t) = P_{HVAC}(t) + P_{EV}^{charging}(t) + P_{ESS}^{charging}(t) + P_{load}(t) \tag{4.3}$$

$$P_{grid}(t) + P_{PV}(t) + P_{FC}(t) + P_{ESS}^{discharging}(t) + P_{EV}^{discharging}(t) = P_{HVAC}(t) + P_{load}(t) \tag{4.4}$$

$$P_{grid}(t) + P_{PV}(t) + P_{FC}(t) + P_{EV}^{discharging}(t) = P_{HVAC}(t) + P_{ESS}^{charging}(t) + P_{load}(t) \tag{4.5}$$

    where $P_{PV}(t)$ is the PV generation at time t; $P_{FC}(t)$ is the FC generation at time t; $P_{ESS}^{discharging}(t)$ is the power supplied by ESS during discharging at time t; $P_{HVAC}(t)$ is the power consumption of HVAC at time t; $P_{EV}^{charging}(t)$ is the power consumption of EV during charging at time t; $P_{load}(t)$ is the power consumption of other home appliances at time t; $P_{ESS}^{charging}(t)$ is the power consumption of ESS during charging at time t; $P_{EV}^{discharging}(t)$ is the power supplied by EV during discharging at time t;

  - Constrain of Battery Capacity

$$0 \leq SOC(t) \leq 100\% \tag{4.6}$$

    where $SOC(t)$ is the SOC of ESS and EV at time t.

  - Constrain of Charger Power

$$0 \leq Power_{ESS} \leq 4kW \tag{4.7}$$

$$0 \leq Power_{EV} \leq 6kW \tag{4.8}$$

where $Power_{ESS}$ and $Power_{EV}$ are the power of ESS and EV during charging and discharging.

– Residents' Preference

$$SOC(target) \leq SOC(final) \tag{4.9}$$

where $SOC(target)$ is the target SOC of EV; $SOC(final)$ is the SOC of EV at departure time in the morning.

$$T_{min} \leq T_{in}(t) \leq T_{max} \tag{4.10}$$

where $T_{in}(t)$ is the indoor temperature at time t; T_{min} and T_{max} are the minimum and maximum acceptable indoor temperature based on PMV [30].

4.2 Joint Electric Vehicle and Thermal Comfort Optimization Scheme

In this section, the scheme is proposed for each season. The joint EV and thermal comfort (TC) optimization (JET) scheme for smart homes can determine the best charging and discharging time in order to minimize the cost while considering the residents' thermal comfort. The algorithm of the scheme and the comparison between related works and my scheme are show in this section. The temperature of outdoor, living room, master bedroom, bedroom1 and bedroom2 of iHouse and the PV generation are also listed in this section.

4.2.1 JET Algorithm

My scheme is proposed based on the Fig 4.1 and the algorithm of the scheme is in algorithm 1. For best comfort scheme, $T^{season}_{room} = T^{season}_{lowerbound} = T^{season}_{upperbound}$. For optimal scheme, $T^{season}_{lowerbound} < T^{season}_{room} < T^{season}_{upperbound}$. For tolerable comfort JET scheme, $T^{tolerable}_{lowerbound} < T^{season}_{room} < T^{tolerable}_{upperbound}$.

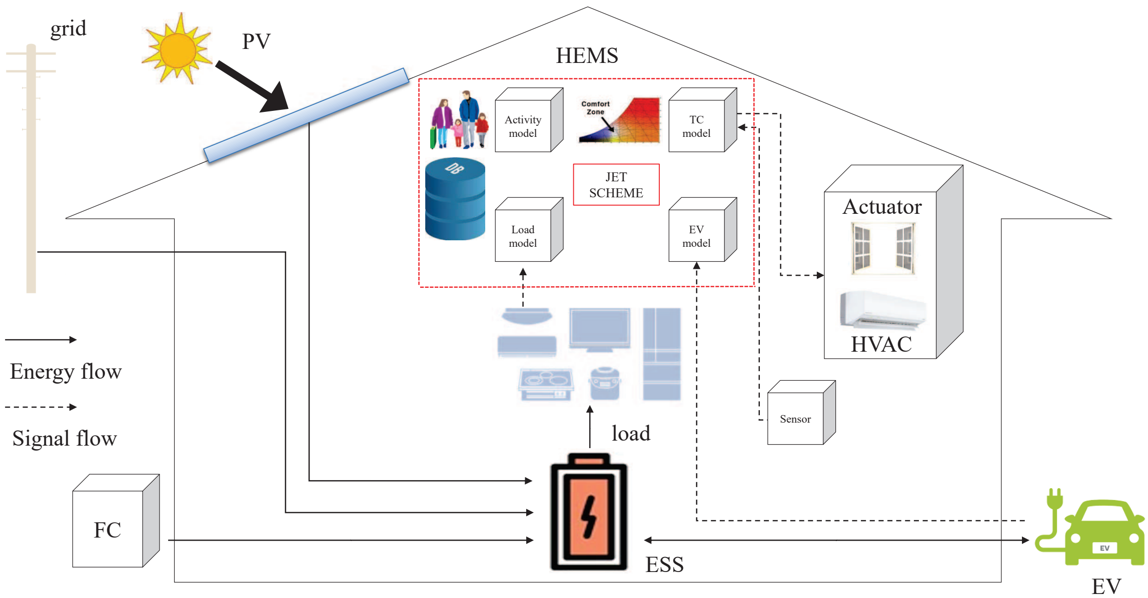

Figure 4.1: JET scheme

4.2.2 Flow of JET Algorithm

The flowchart of JET is shown if Fig 4.2. In each time interval, the JET algorithm starts by gathering data, which include the power consumption of all appliances, power generation of PV and FC, indoor and outdoor temperatures, electricity price and energy of ESS and EV. Then, the JET algorithm checks if the room temperatures is between $T^{season}_{lowerbound}$ and $T^{season}_{upperbound}$ or not. If the room temperature is not in a range of $T^{season}_{lowerbound}$ to $T^{season}_{upperbound}$, the JET will turn on the HVAC to meet the comfort demand and compute the power of HVAC. If the room temperature is in a range of $T^{season}_{lowerbound}$ to $T^{season}_{upperbound}$, no action is taken here. After it, the total power consumption is compared with the power

Algorithm 1 JET Algorithm

Definition: P is power, T is temperature, C is cost
k is time interval of charging or discharging, E is energy
Input: P
Output: an optimum value of C
Begin
Set $E_{ESS}(0) = 0$, $E_{EV}(t) = E_{EV}^{max}(t) - E_{EV}^{used}(t)$, $T_{upperbound}^{season}$, $T_{lowerbound}^{season}$, T_{set}^{season}
If $T_{room}(t) > T_{upperbound}^{season}$ or $T_{room}(t) < T_{lowerbound}^{season}$
$P_{HVAC}(t) = \frac{1.08 \cdot CFM(T_{set}^{season} - T_{room}(t))}{COP \cdot k}$
else $P_{HVAC}(t) = 0$
Calculate $P_{supply}(t) = P_{PV}(t) + P_{FC}(t)$ and $P_{demand}(t) = P_{HVAC}(t) + P_{load}(t)$
If $P_{supply}(t) > P_{demand}(t)$
$E_{ESS}(t) = E_{ESS}(t-1) + k \cdot (P_{supply}(t) - P_{demand}(t))$ // ESS is charging
else if $E_{ESS}(t-1) > k \cdot (P_{demand}(t) - P_{supply}(t))$ //ESS is enough
$E_{ESS}(t) = E_{ESS}(t-1) + k \cdot (P_{supply}(t) - P_{demand}(t))$ ESS is discharging
else if $E_{EV}(t-1) > k \cdot (P_{demand}(t) - P_{supply}(t)) - E_{ESS}(t-1)$ // EV is enough
$E_{EV}(t) = E_{EV}(t-1) + E_{ESS}(t-1) +$
$k \cdot (P_{supply}(t) - P_{demand}(t))$ // EV is discharging
else $P_{grid}(t) = k \cdot (P_{demand}(t) - P_{supply}(t)) - E_{ESS}(t-1) - E_{EV}(t-1)$
If $price(t) \leq price_{min}$
$E_{ESS}(t) = P_{grid}(t) \cdot k$
$E_{EV}(t) = P_{grid}(t) \cdot k$
$C_{min} = \sum_{0}^{24} price(t) \cdot P_{grid}(t) \cdot k$
End

generation of PV and FC, if power generation of PV and FC is greater than the total power consumption, the JET will charge ESS. If power generation of PV and FC is lower than the total power consumption, the JET will discharge ESS to meet the demand, if ESS is not enough to meet the demand, JET will discharge ESS and EV to meet the demand, if it still can't meet the demand, then JET will purchase energy from power grid. At last, when the price is lowest, JET will charge ESS and EV.

4.2.3 Comparison with the Related Work

Paper [5], considered the residents' thermal comfort by using the price that aggregator has to pay when the temperature deviates from the desired temperature to compute the cost.

But for my scheme, I used PMV parameters to improve residents' thermal comfort. The comparison between with and without the scheme and situations of different comfort are shown in Fig 4.3 and Fig 4.4.

4.2.4 Temperature and PV Generation of iHouse

- Spring

  In spring, it is not necessary to open HVAC system to meet the demand of comfort. So, the joint optimization scheme just considers the cost and the demand of EV.

- Summer

  In summer, the comfortable is between $20°C$ to $22°C$. The Fig 4.8 shows that only the temperature of living room can not meet the demand of comfort. So, the joint optimization scheme must consider the cost and the demand of EV and HVAC in living room in order to keep the temperature of living room in a suitable range.

- Autumn

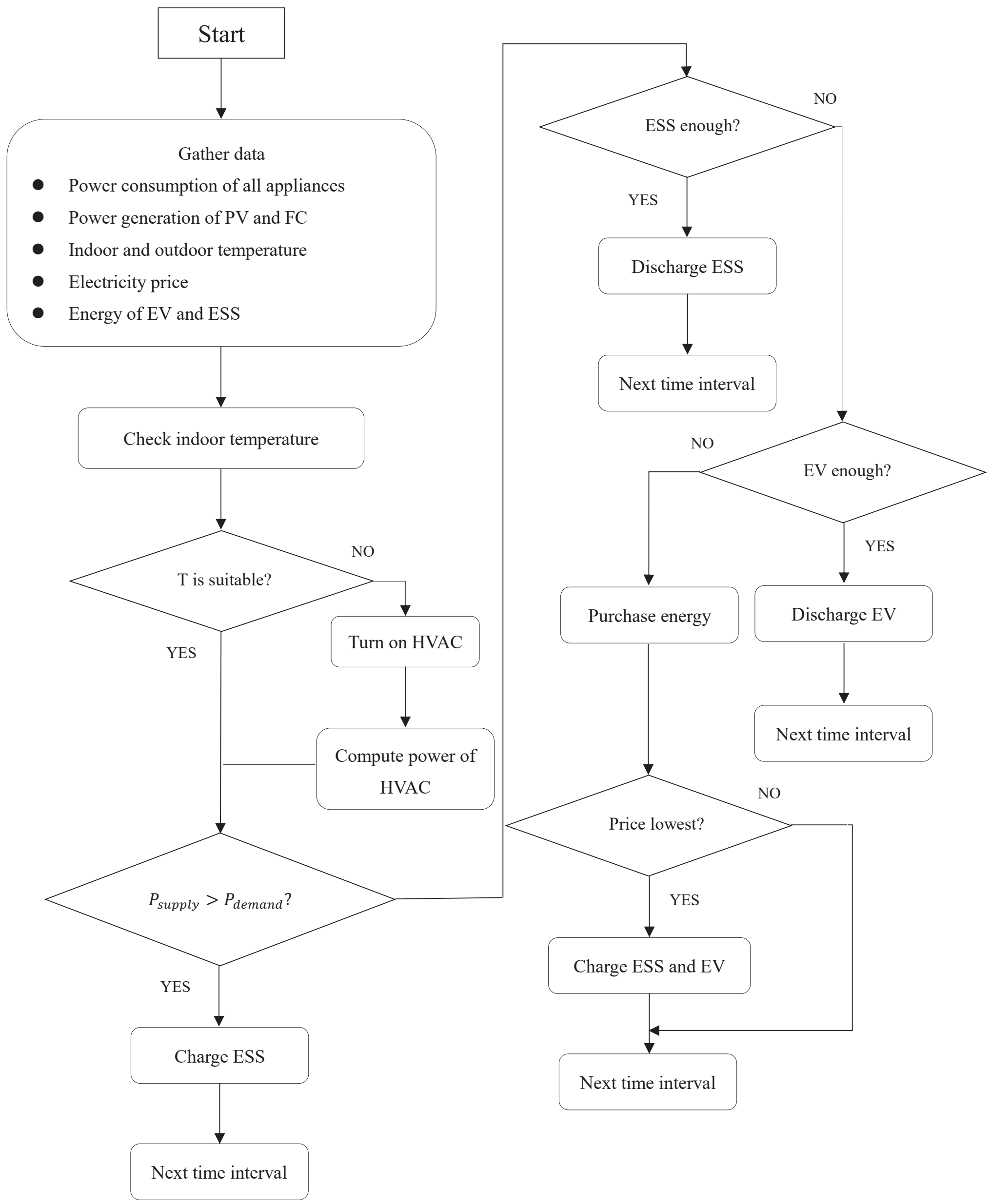

Figure 4.2: Flowchart of JET

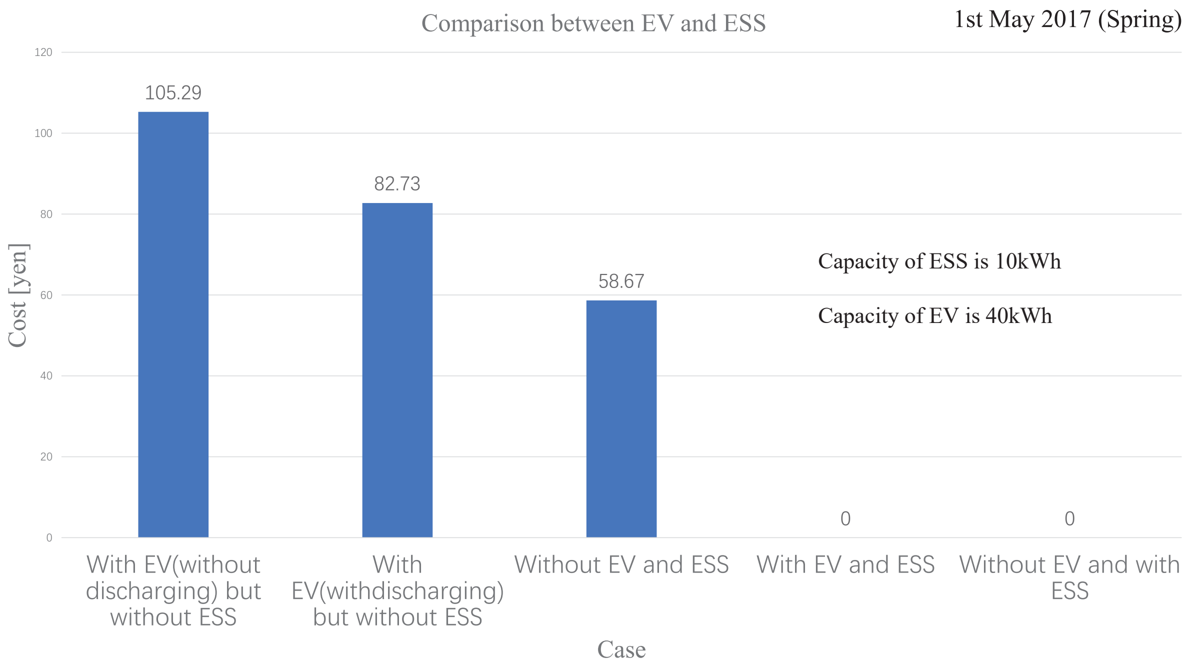

Figure 4.3: Comparison between with and without the scheme

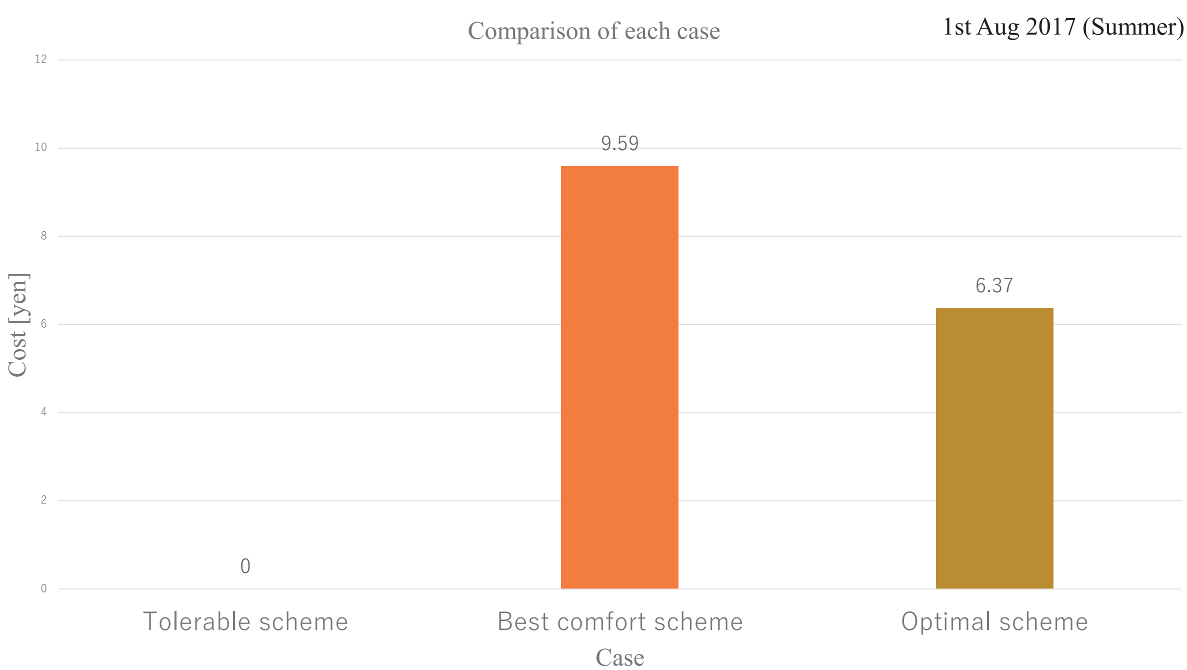

Figure 4.4: Comparison between the situations of different comfort

In autumn, it is not necessary to open HVAC system to meet the demand of comfort

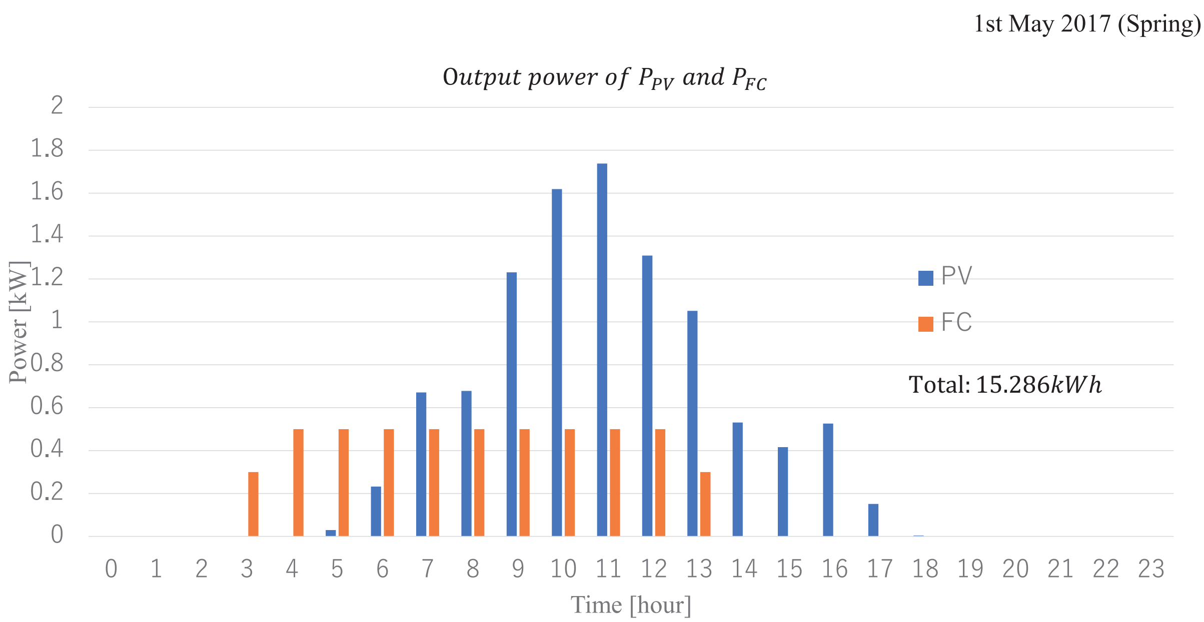

Figure 4.5: Output power of PV and FC in spring

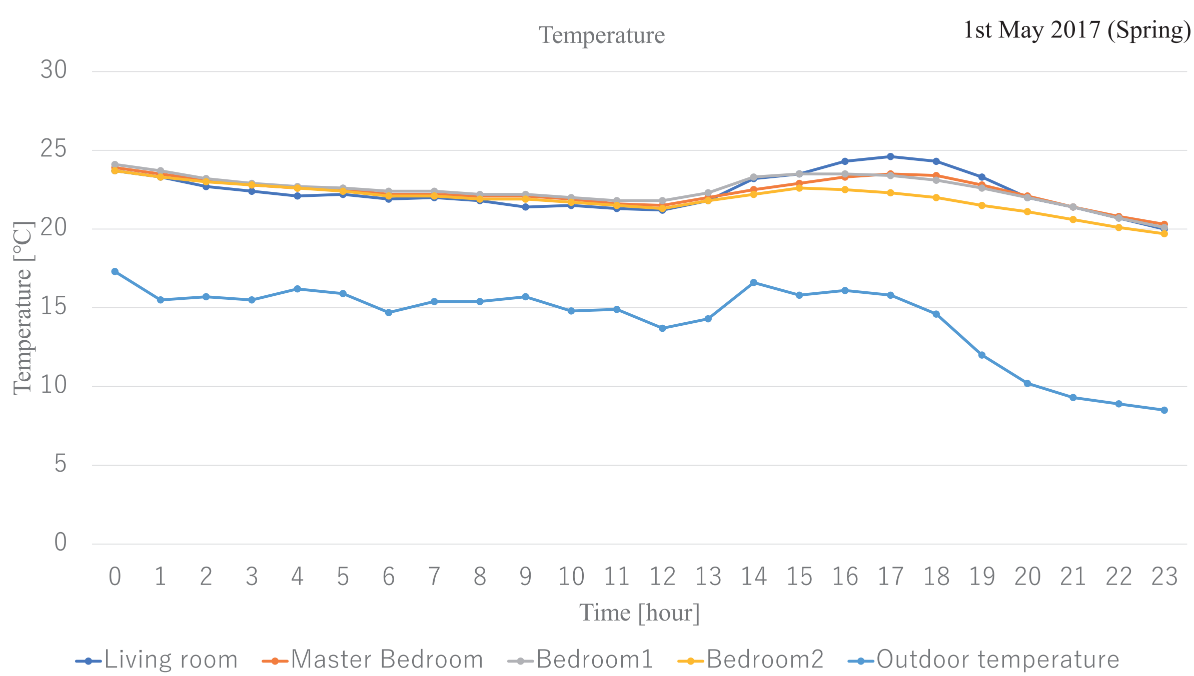

Figure 4.6: Temperature in spring

too. So, the joint optimization scheme just considers the cost and the demand of EV.

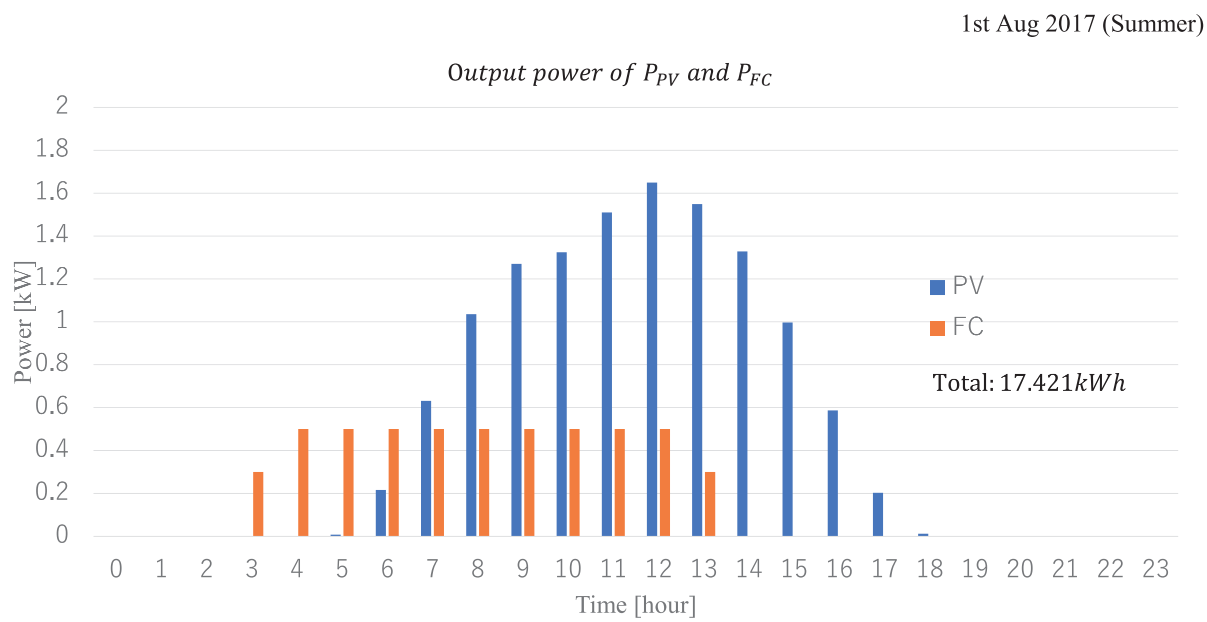

Figure 4.7: Output power of PV and FC in summer

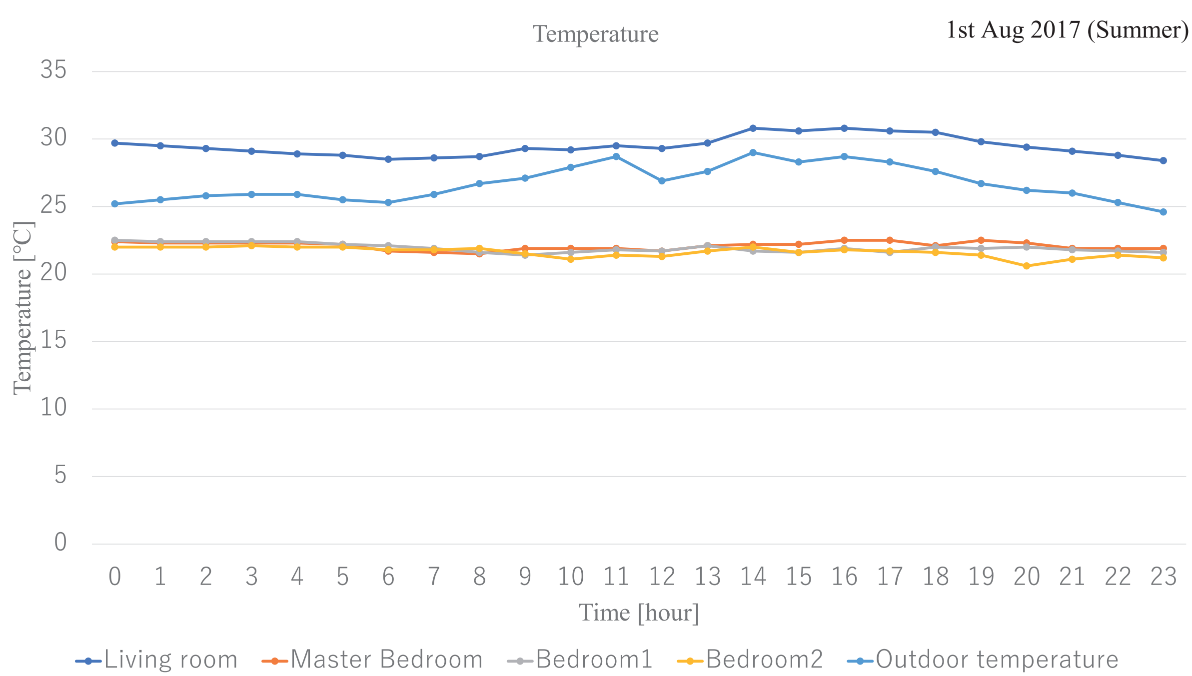

Figure 4.8: Temperature in summer

- Winter

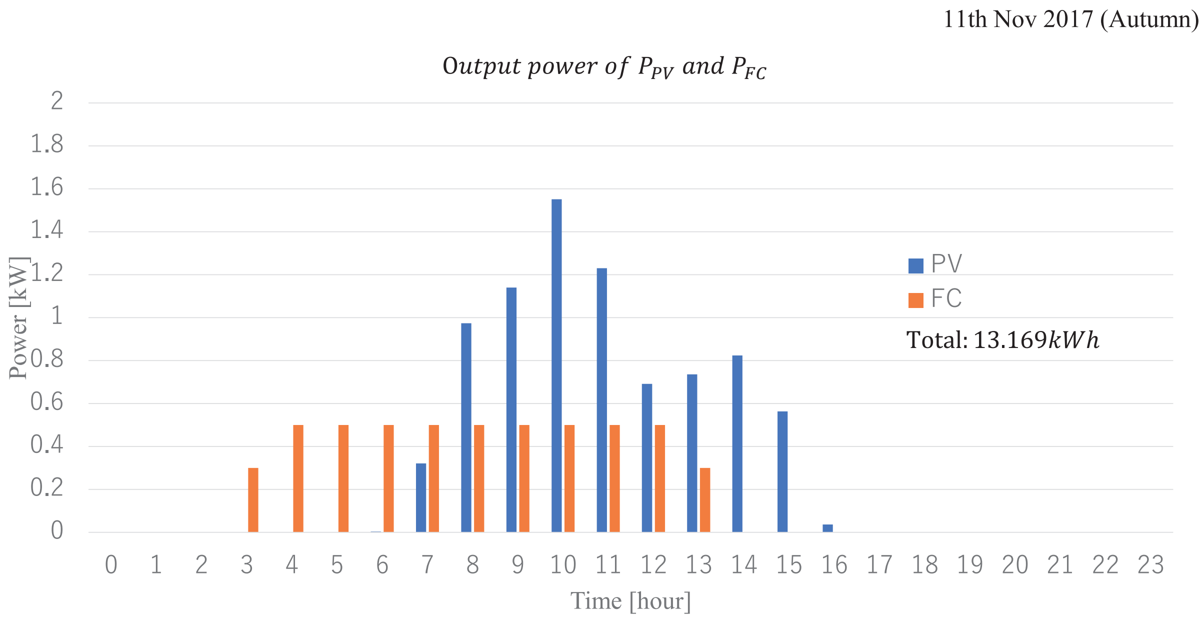

Figure 4.9: Output power of PV and FC in autumn

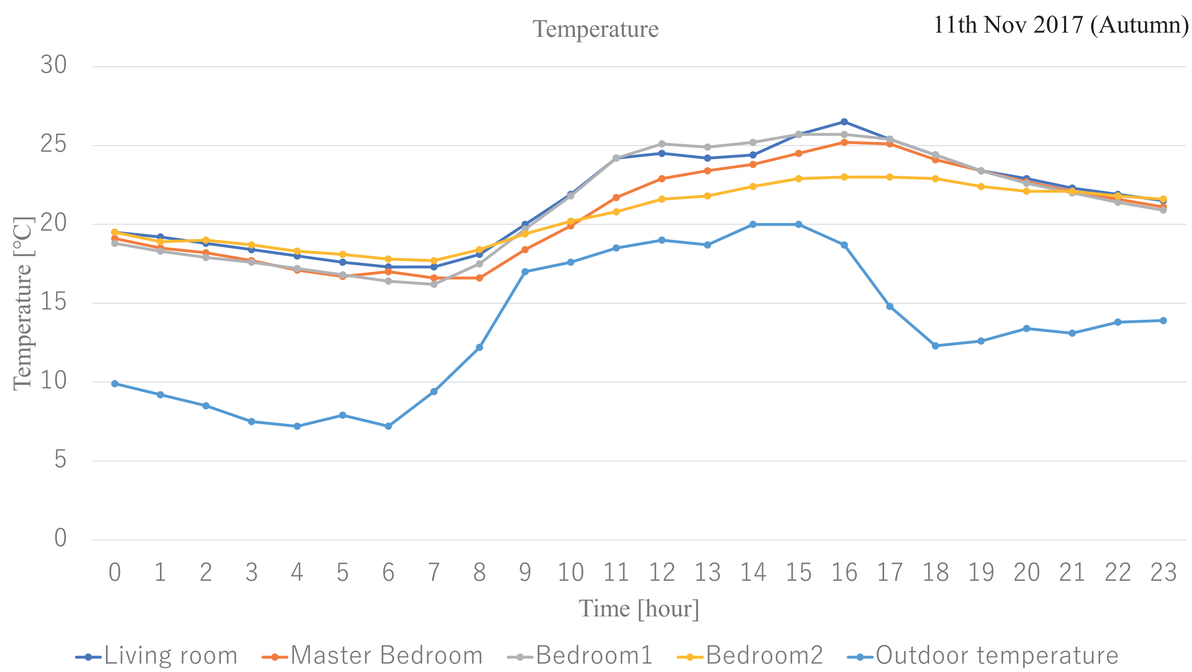

Figure 4.10: Temperature in autumn

In winter, the comfortable is between 19°C to 21°C. The Fig 4.12 shows that the temperature of all rooms can not meet the demand of comfort. So, the joint

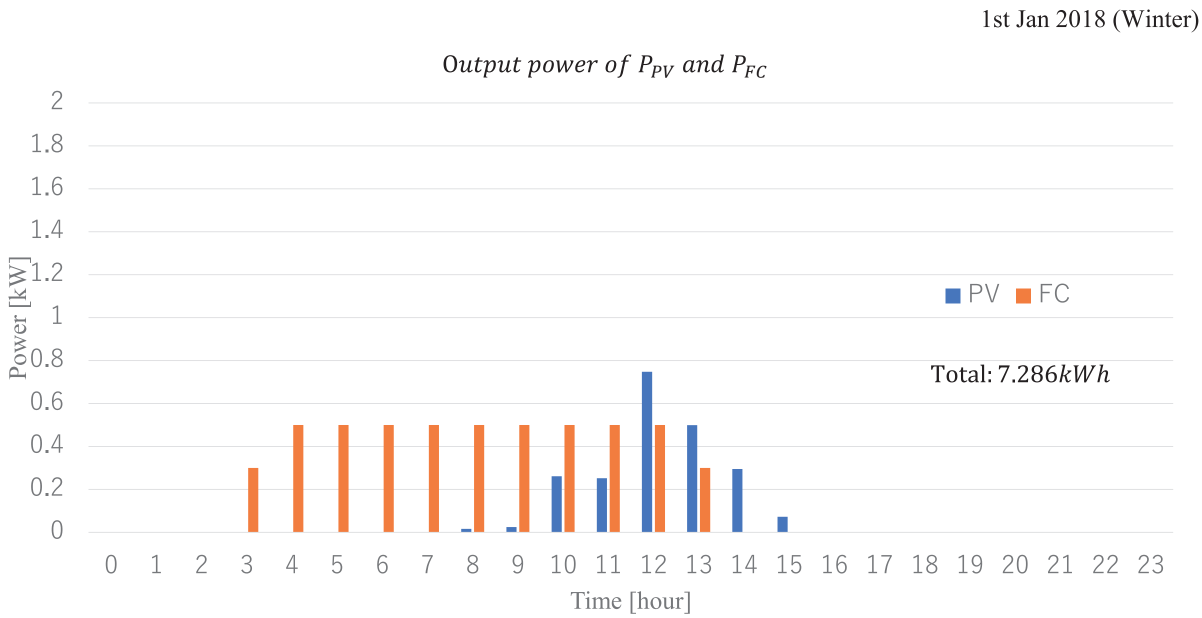

Figure 4.11: Output power of PV and FC in winter

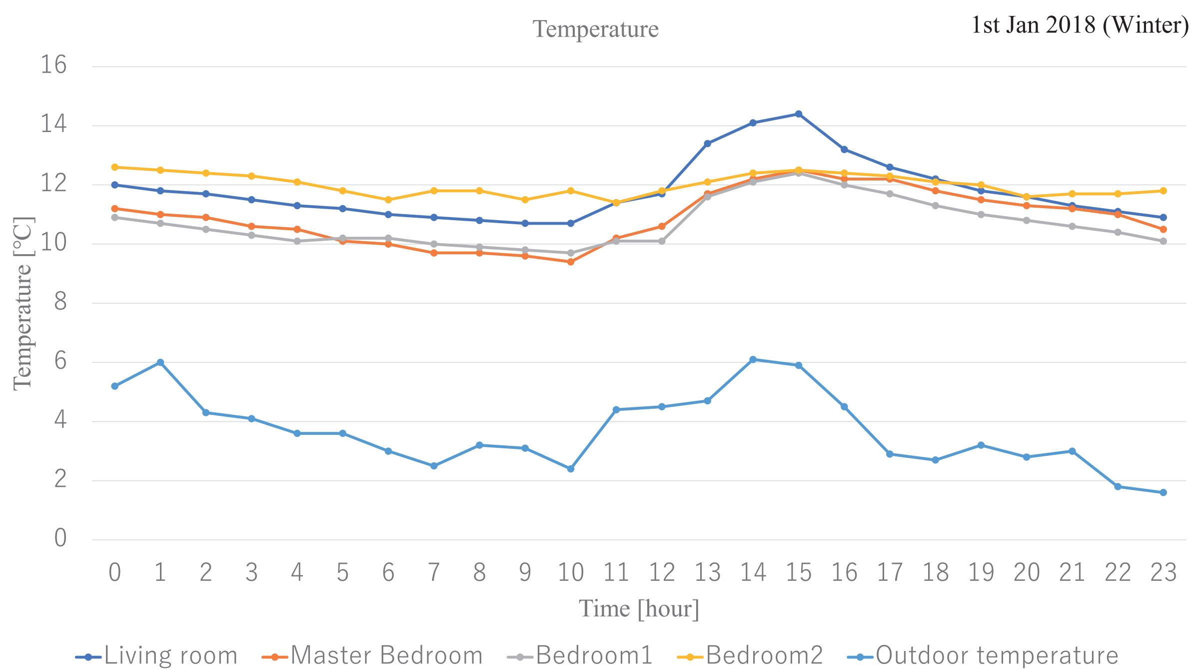

Figure 4.12: Temperature in winter

optimization scheme must consider the cost and the demand of EV and each HVAC in ihouse in order to keep the temperature in a suitable range.

4.3 Summary

For spring and autumn, the schemes are proposed based on the cases of with EV discharging and without EV discharging, the impacts of the capacity of EV and ESS on cost are also shown in next chapter. For summer and winter, the cases of considering the demand of comfort and without considering the demand of comfort are also shown.

Chapter 5

Evaluation and Analysis

In this chapter, the schemes are proposed for each season. The impacts of capacity of EV and ESS on cost and the cost comparison of each case are shown in each subsection. For, summer and winter, two schemes considering residents' comfort and the cost comparison between them are also shown.

5.1 Simulation Parameters and Settings

In this research, the simulation environment is MATLAB R2018b, the raw data of outside and inside temperature are obtained from iHouse, the date of each season is 1st Jan 2018 (winter), 1st Aug 2017 (summer), 1st May 2017 (spring), 11th Nov 2017 (Autumn).

5.2 Numerical Results

5.2.1 Spring

For spring, the charging and discharging power of ESS without and with EV are shown in Fig 5.1 and 5.2 respectively. The results of total cost incurred with ESS and EV are shown in Fig 5.3 and 5.4. The cost of each case is shown in Fig 5.5.

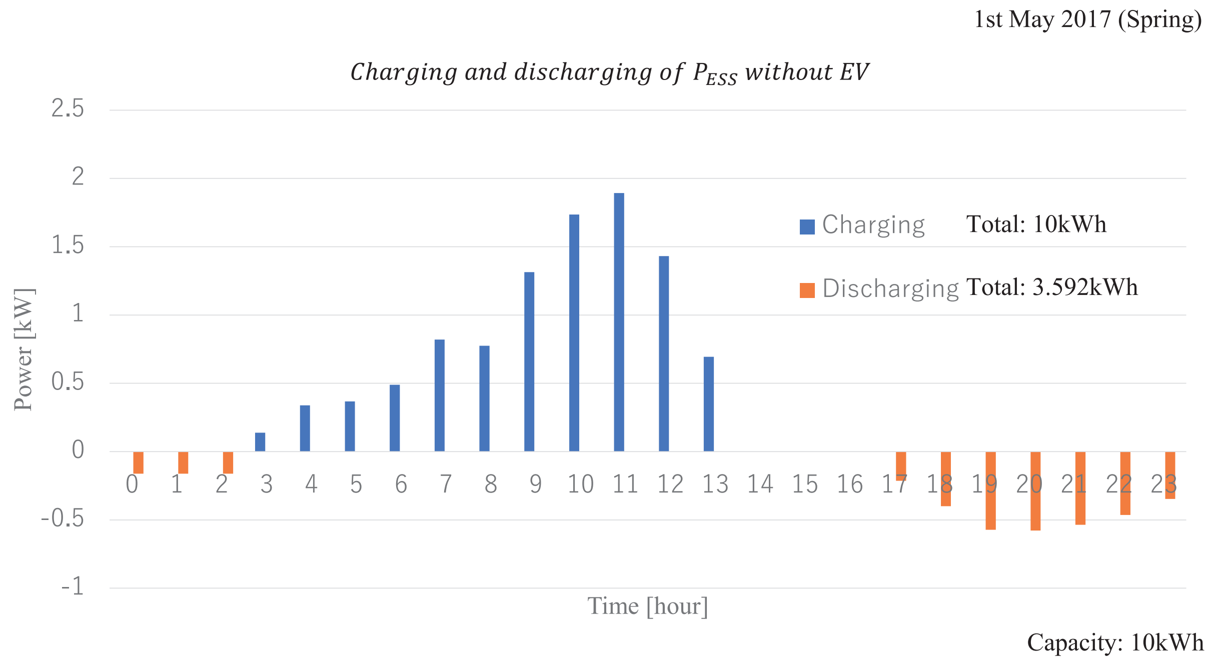

Figure 5.1: Charging and discharging power of ESS without EV in spring

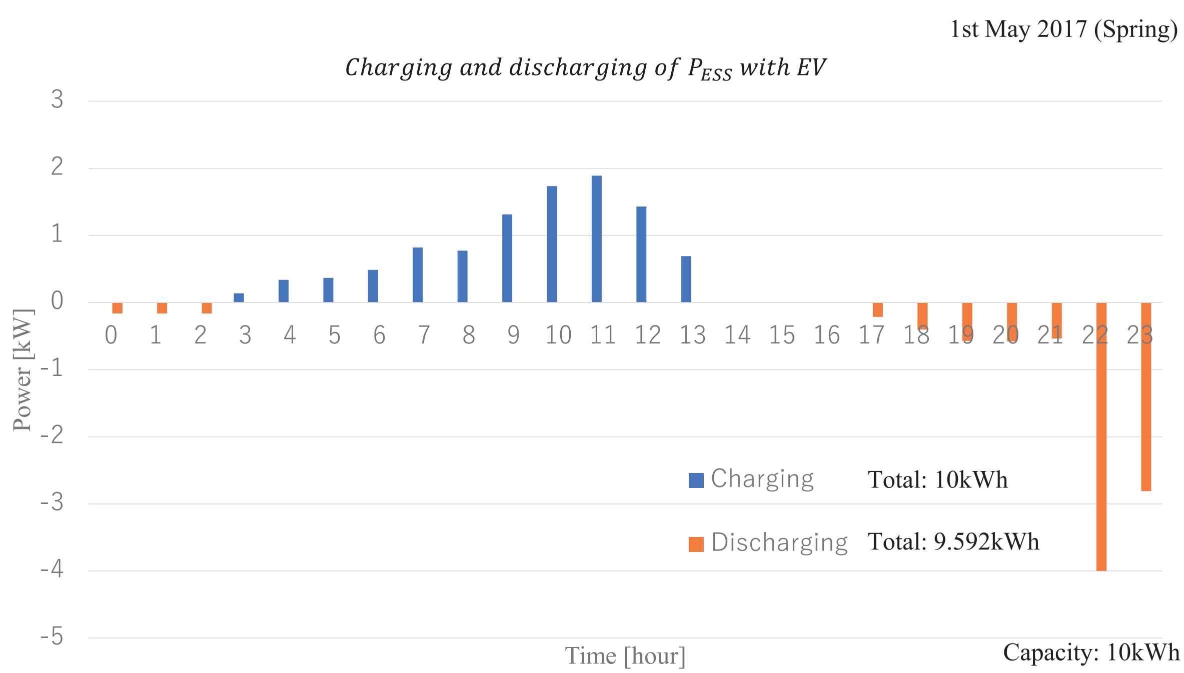

Figure 5.2: Charging and discharging power of ESS with EV in spring

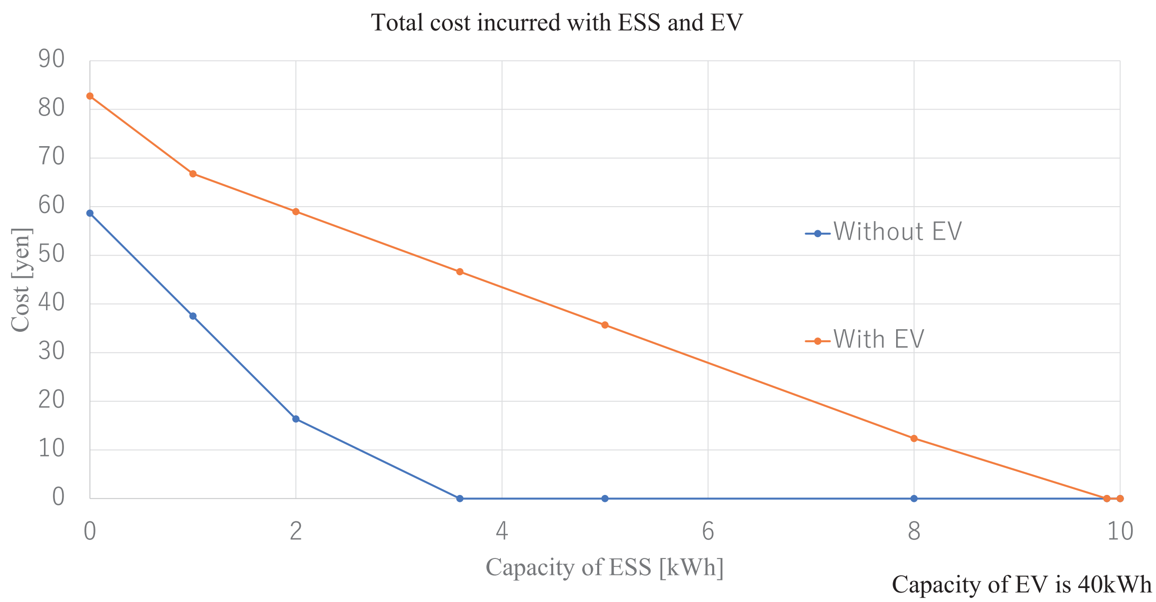

Figure 5.3: Total cost incurred with ESS and EV a

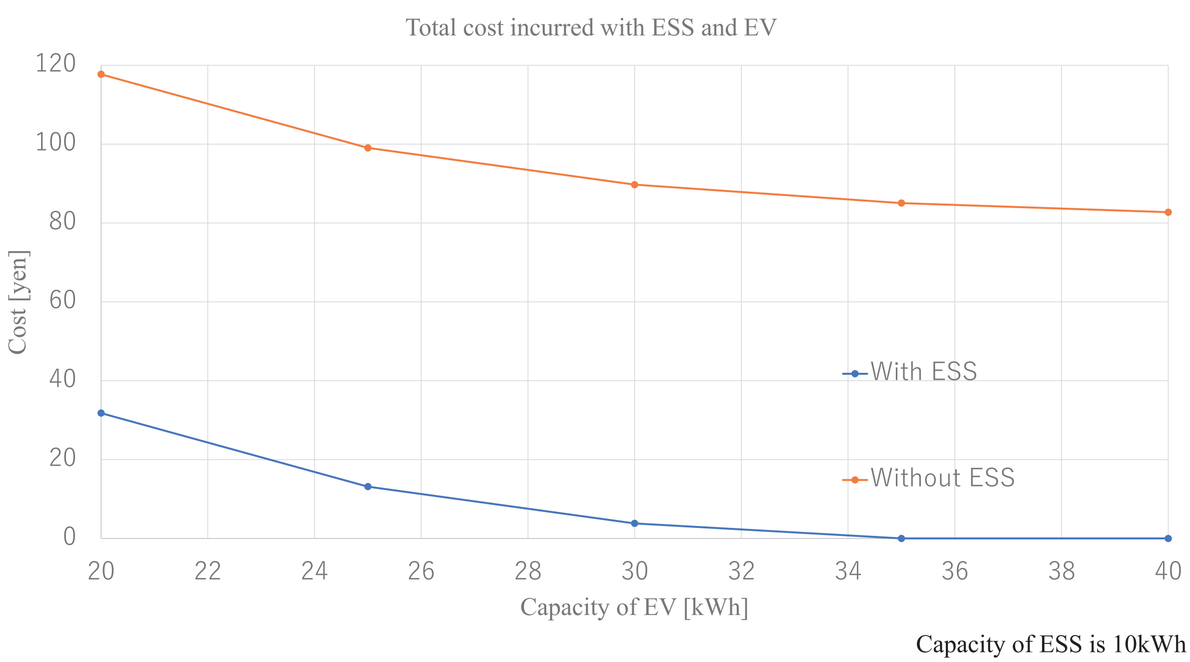

Figure 5.4: Total cost incurred with ESS and EV b

5.2.2 Summer

- Without Considering Residents' Comfort

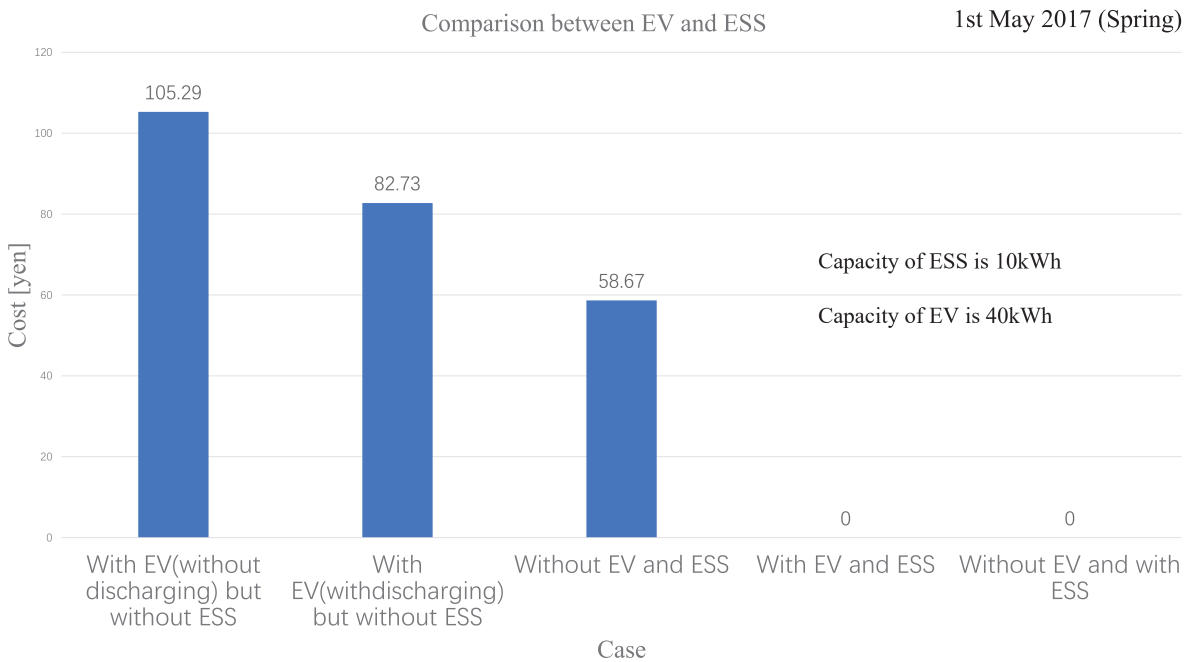

Figure 5.5: Comparison between EV and ESS

For this case, the charging and discharging power of ESS without and with EV are shown in Fig 5.6 and 5.7 respectively. The results of total cost incurred with ESS and EV are shown in Fig 5.8 and 5.9. The cost of each case is shown in Fig 5.10.

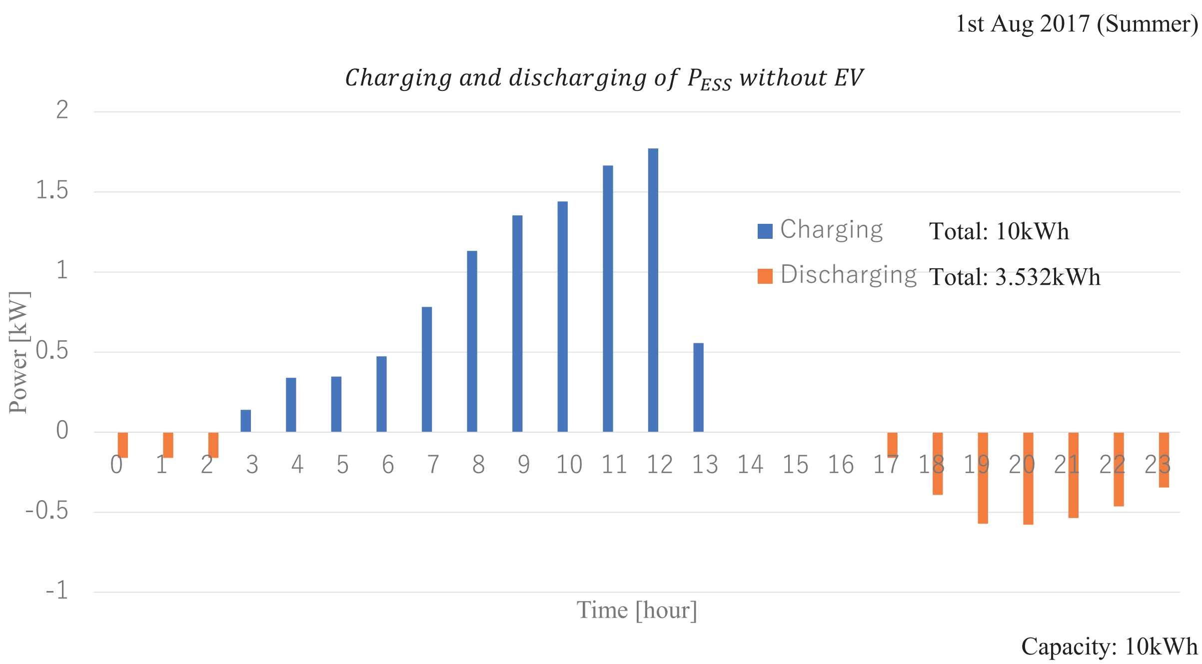

Figure 5.6: Charging and discharging power of ESS without EV in summer

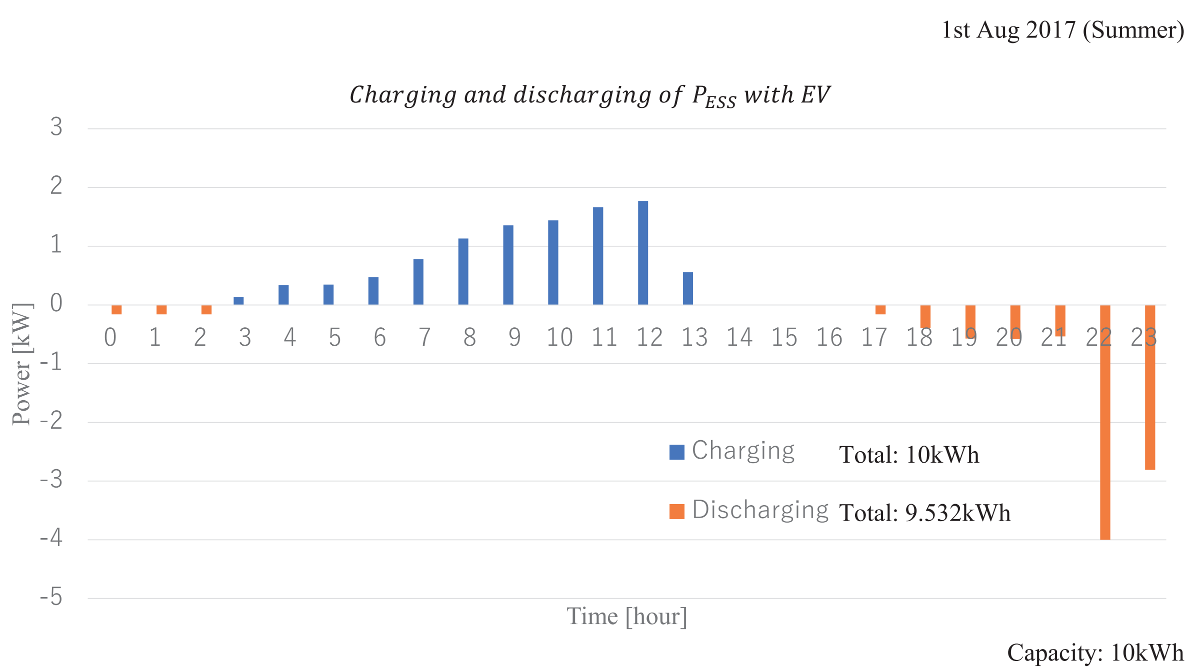

Figure 5.7: Charging and discharging power of ESS with EV in summer

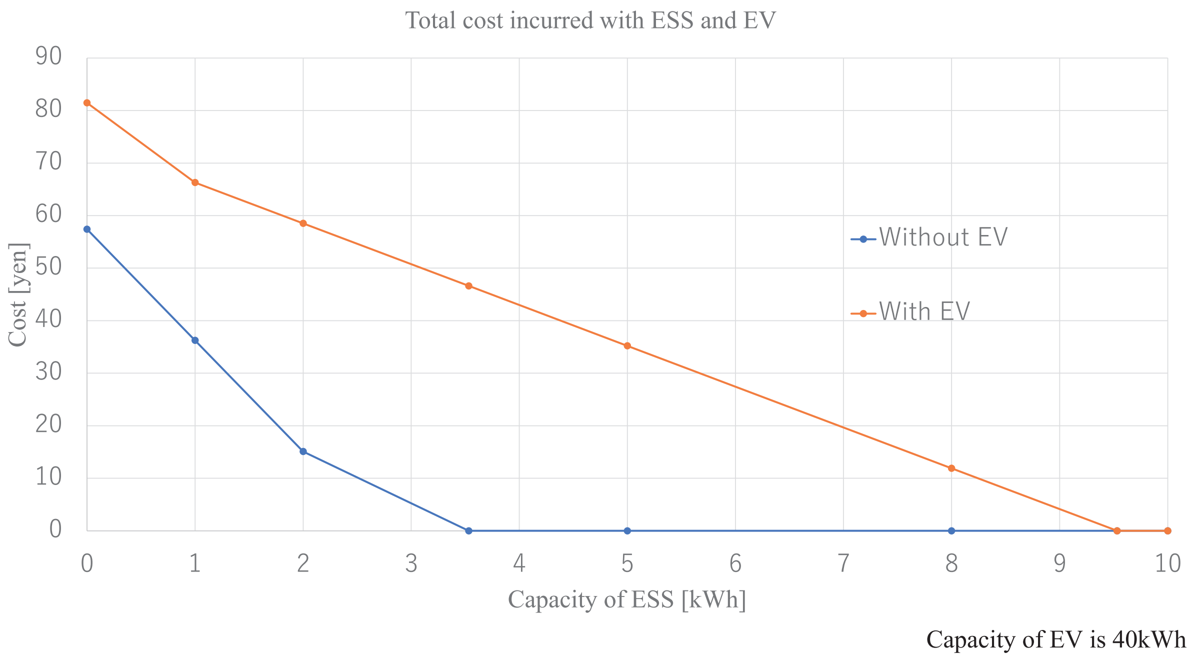

Figure 5.8: Total cost incurred with ESS and EV a

Figure 5.9: Total cost incurred with ESS and EV b

- Considering Residents' Comfort ($21°C$)

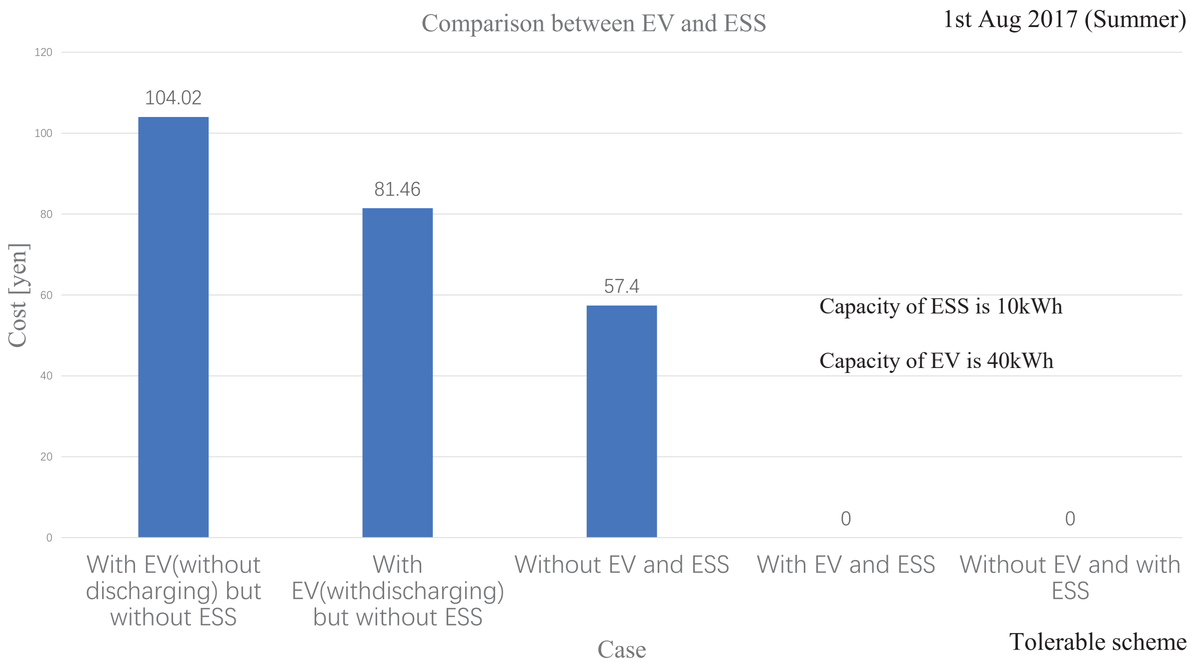

Figure 5.10: Comparison between EV and ESS

For this case, the charging and discharging power of ESS without and with EV are shown in Fig 5.11 and 5.12 respectively. The results of total cost incurred with ESS and EV are shown in Fig 5.13 and 5.14. The cost of each case is shown in Fig 5.15.

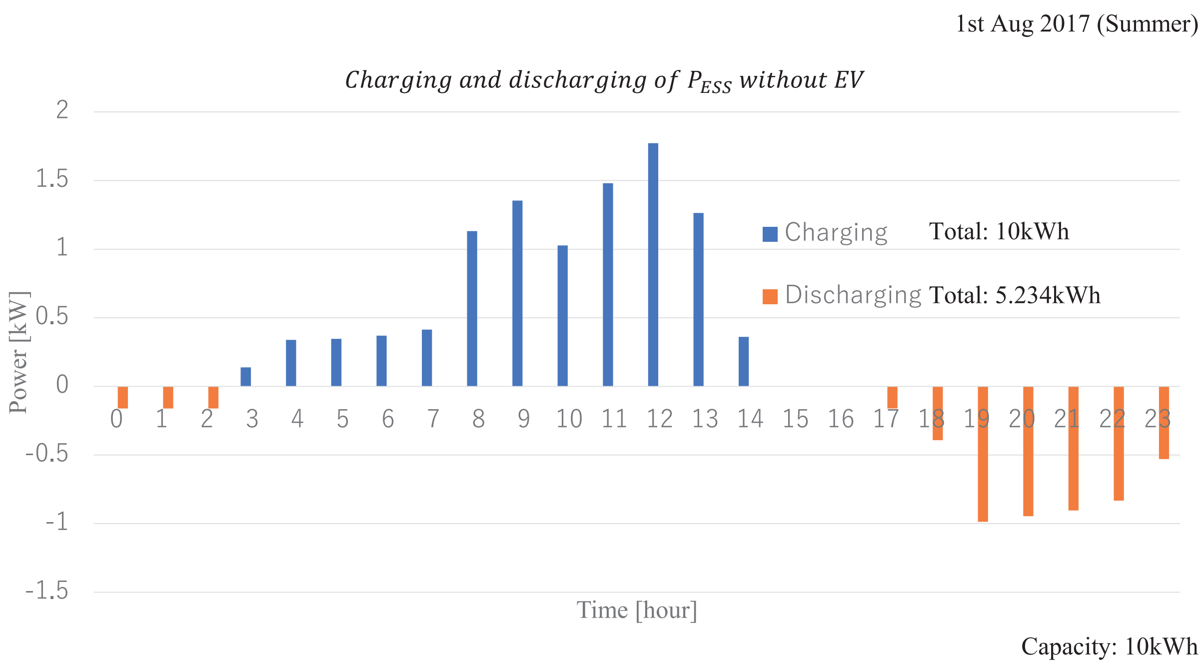

Figure 5.11: Charging and discharging power of ESS without EV in summer

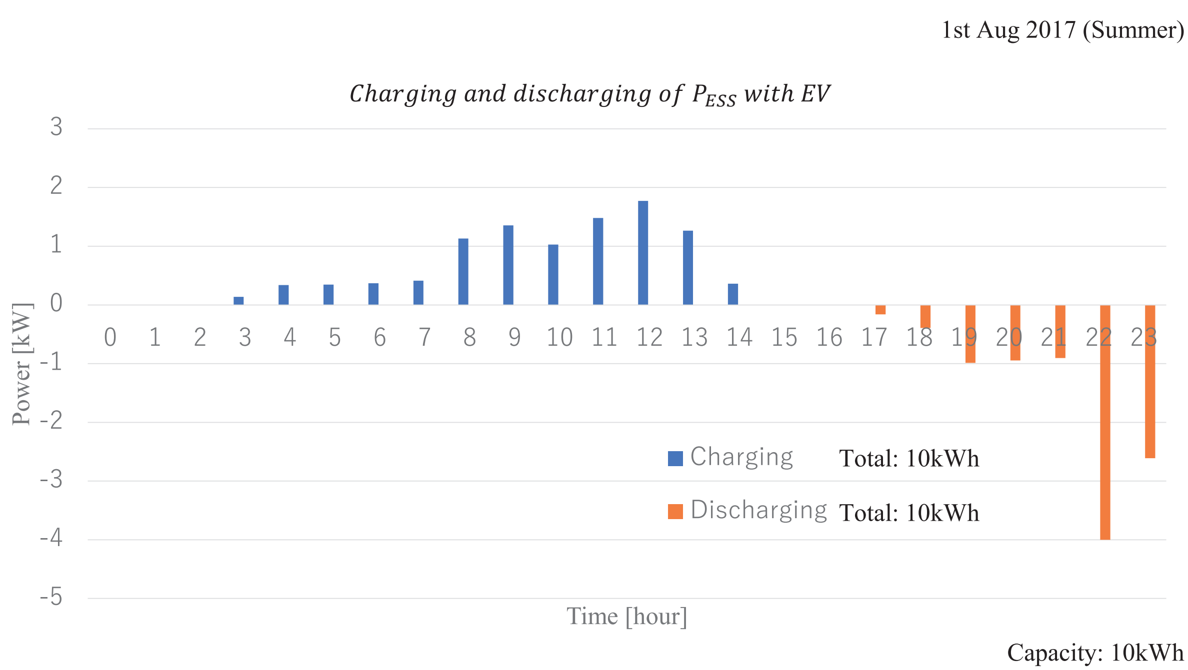

Figure 5.12: Charging and discharging power of ESS with EV in summer

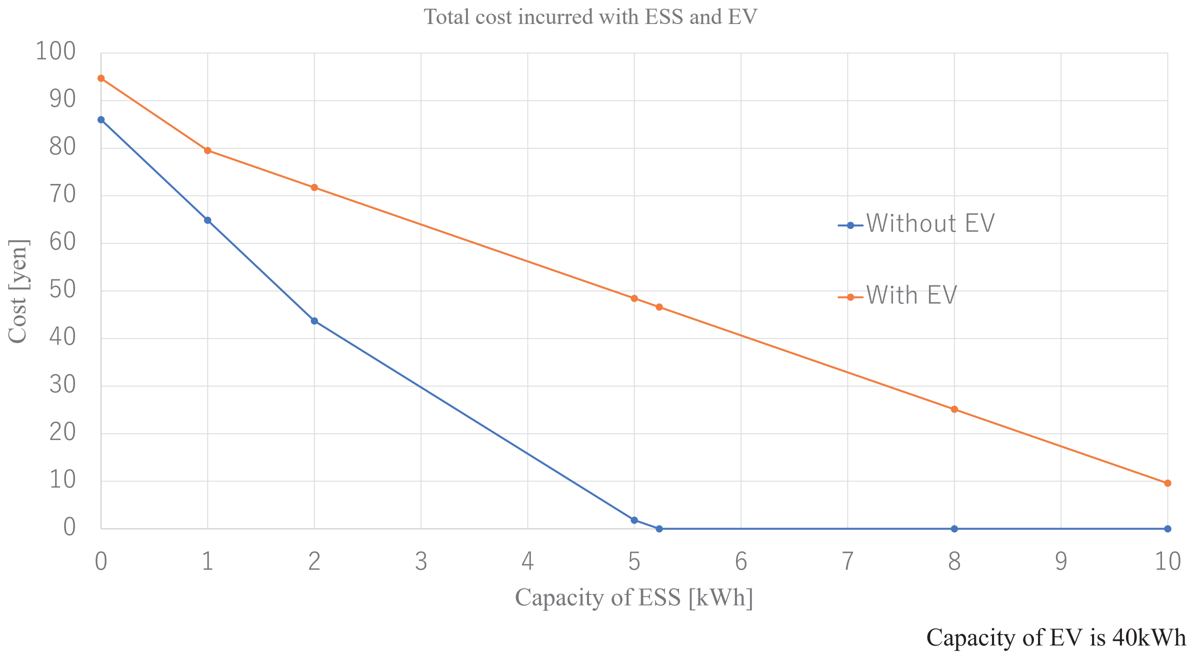

Figure 5.13: Total cost incurred with ESS and EV a

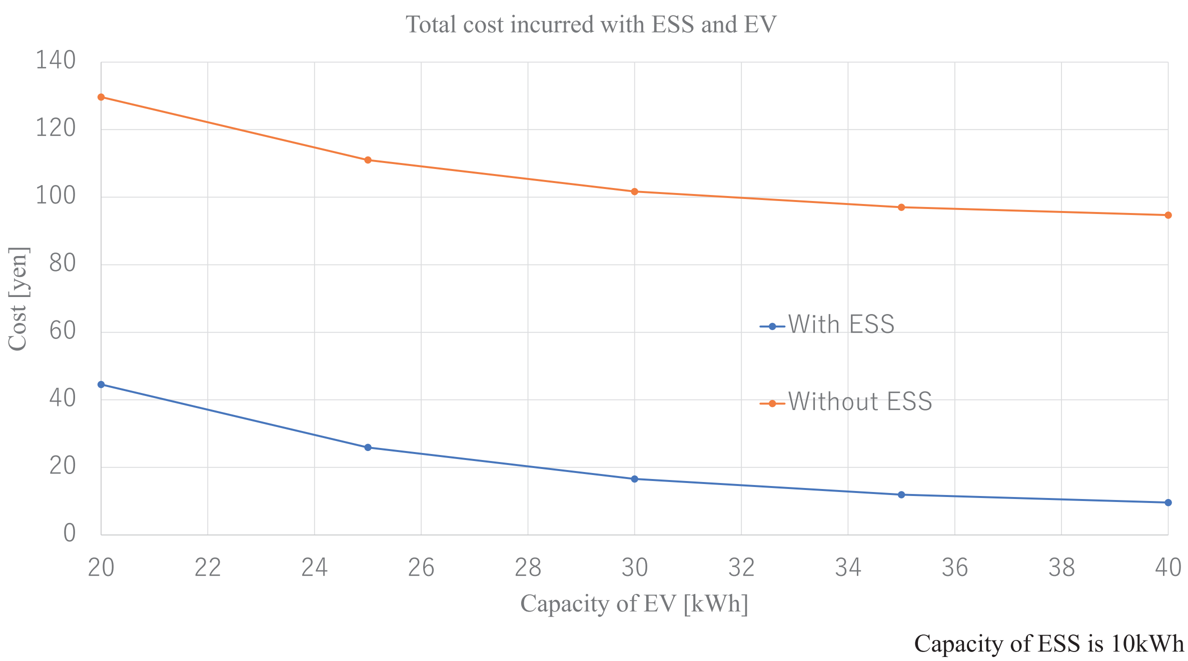

Figure 5.14: Total cost incurred with ESS and EV b

- Considering Residents' Comfort (20°C -22°C)

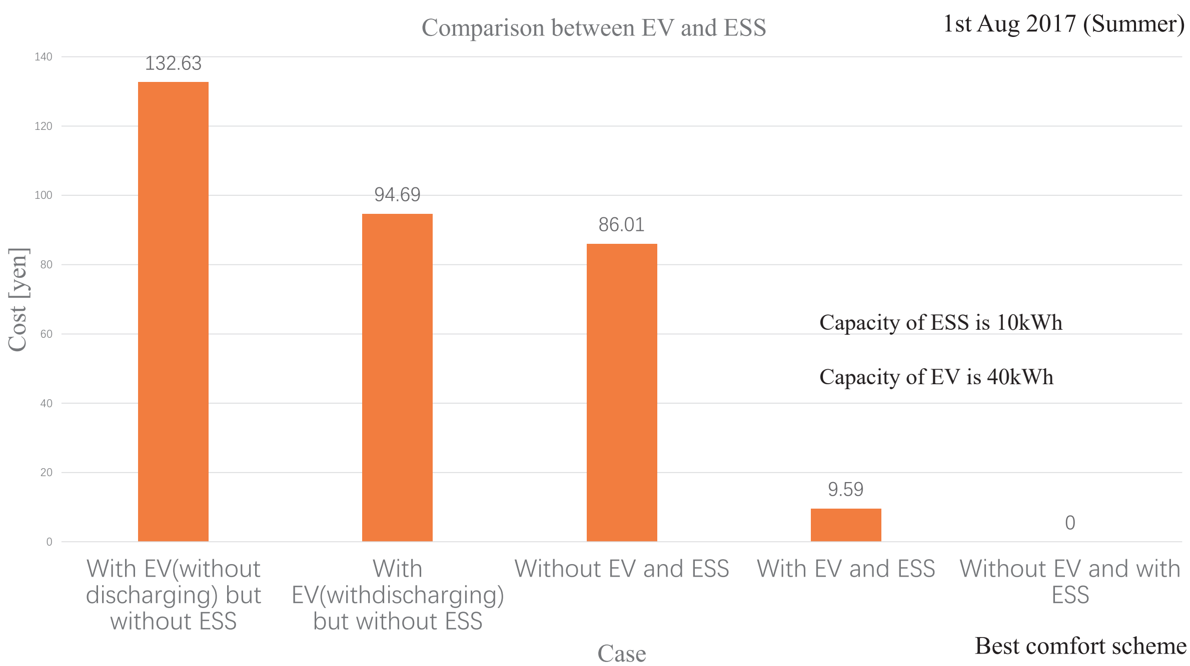

Figure 5.15: Comparison between EV and ESS

For this case, the charging and discharging power of ESS without and with EV are shown in Fig 5.16 and 5.17 respectively. The results of total cost incurred with ESS and EV are shown in Fig 5.18 and 5.19. The cost of each case is shown in Fig 5.20.

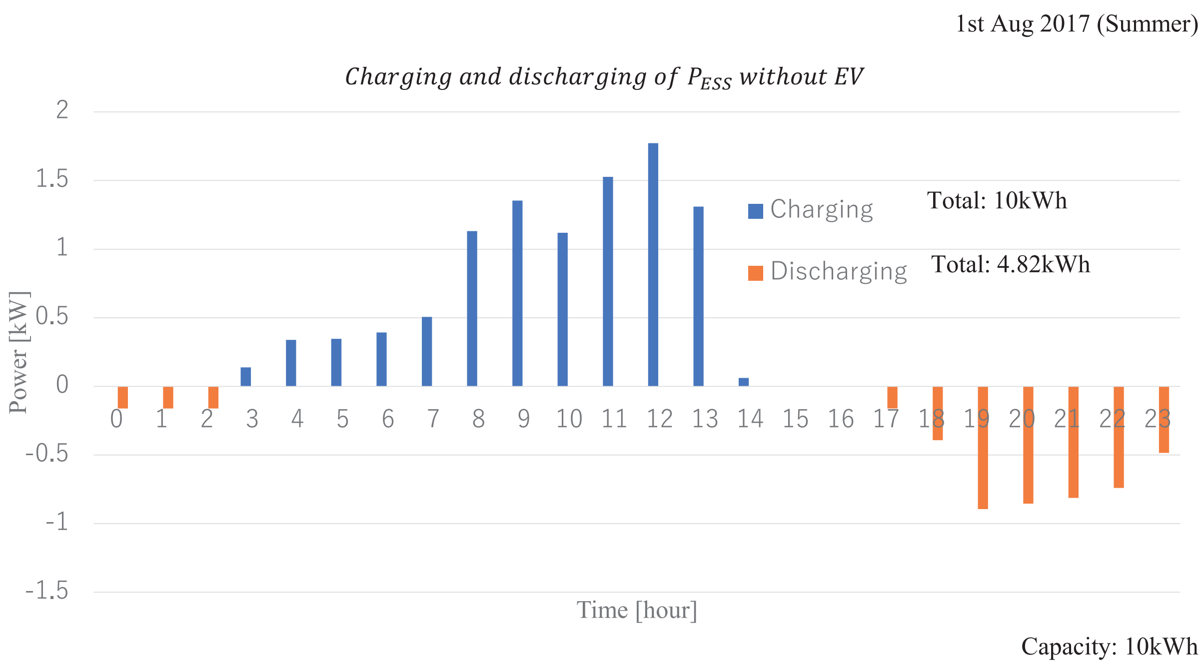

Figure 5.16: Charging and discharging power of ESS without EV in summer

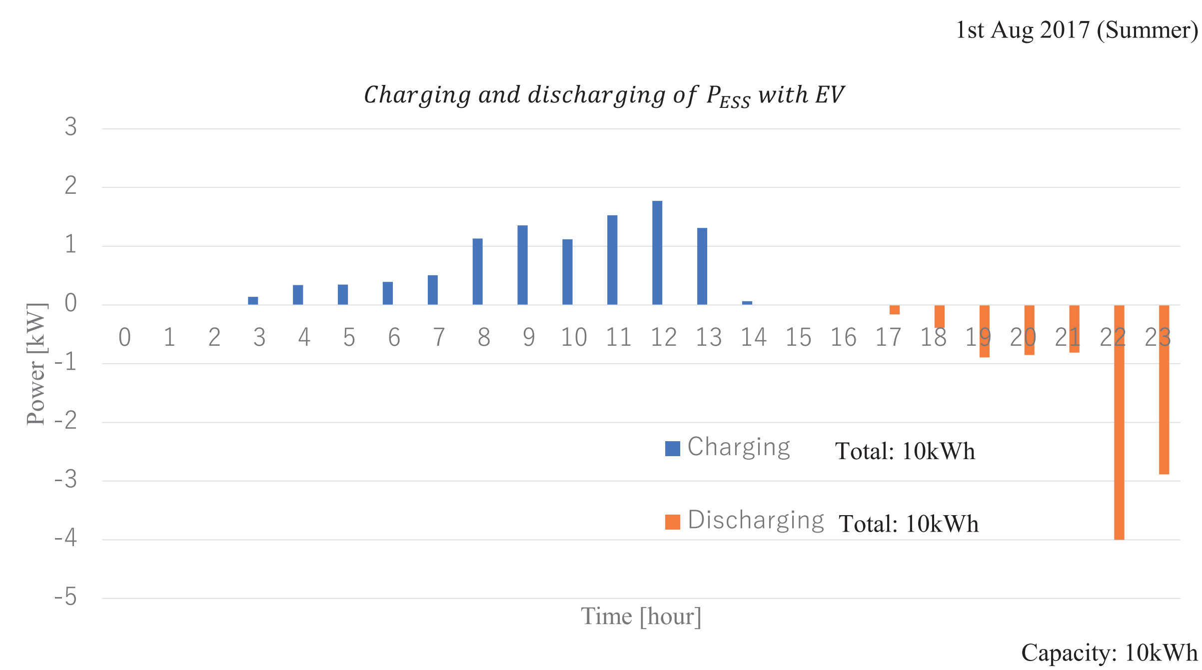

Figure 5.17: Charging and discharging power of ESS with EV in summer

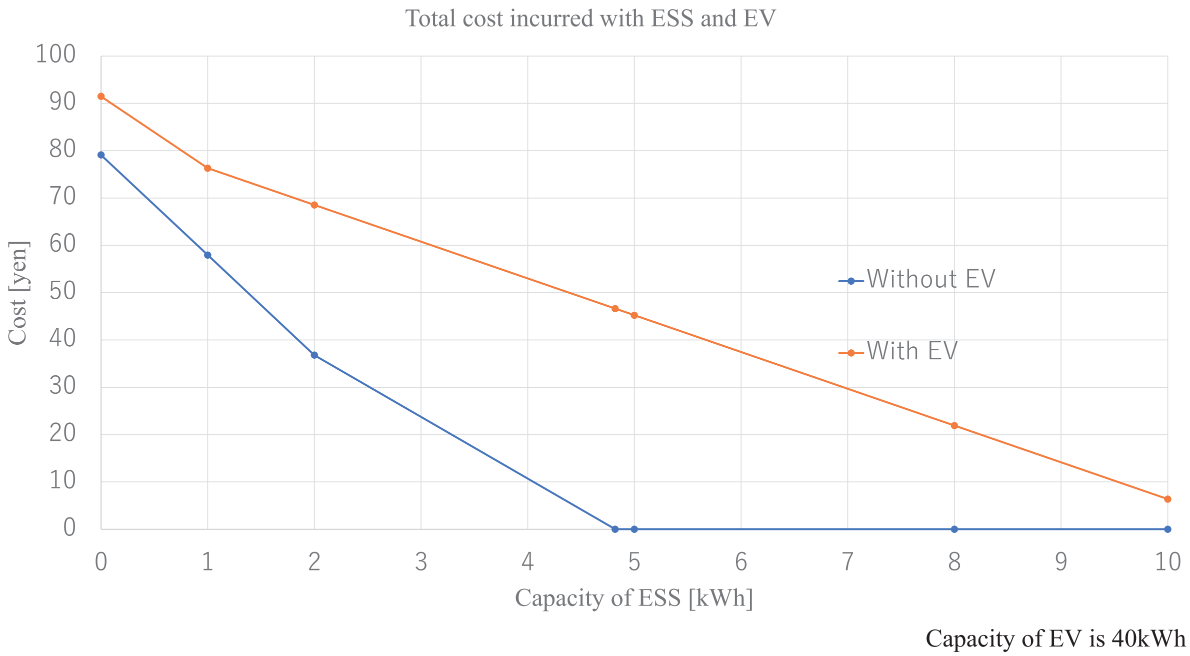

Figure 5.18: Total cost incurred with ESS and EV a

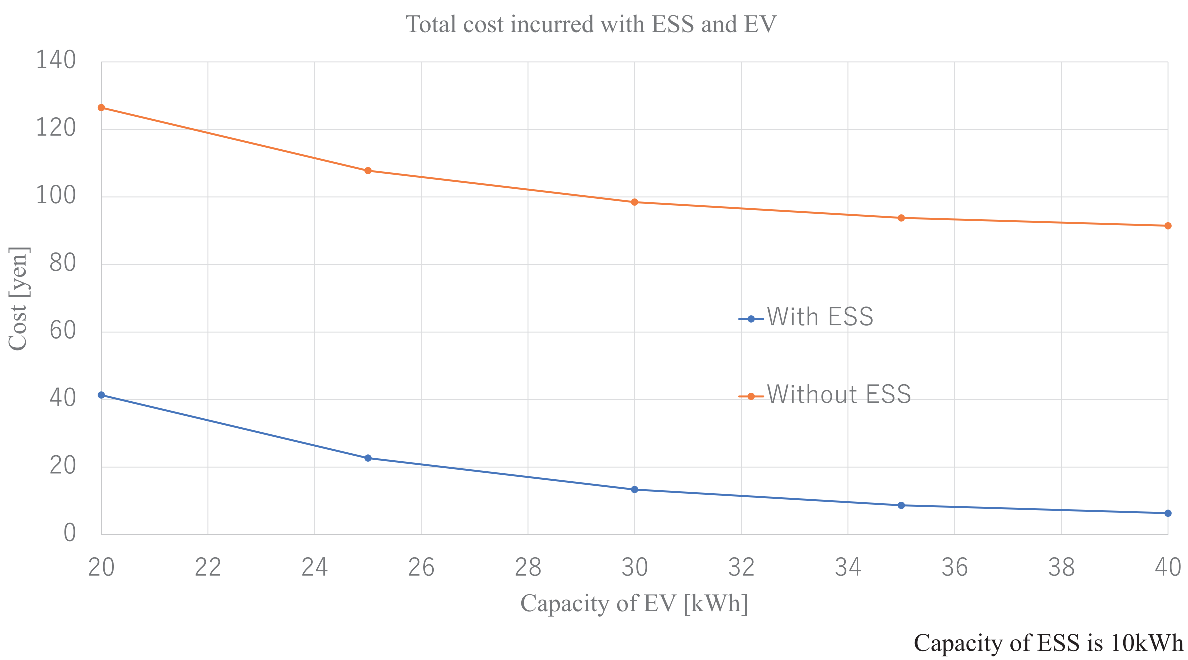

Figure 5.19: Total cost incurred with ESS and EV b

The cost comparison is shown in Fig 5.21

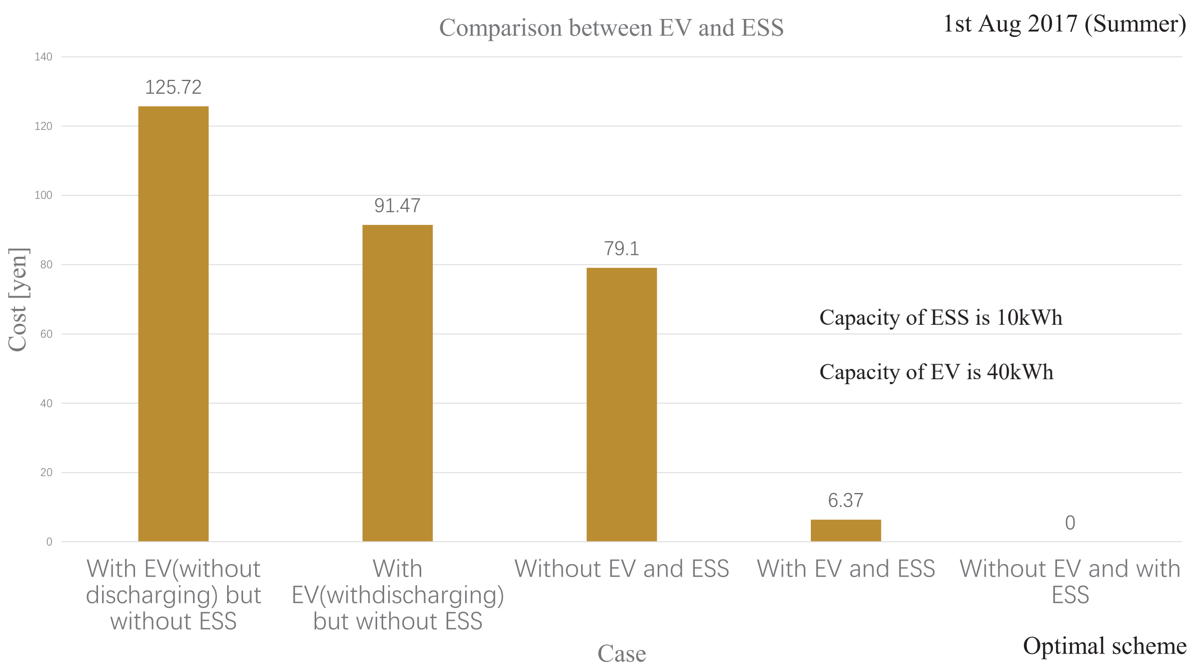

Figure 5.20: Comparison between EV and ESS

Figure 5.21: Comparison between considering Residents' comfort and without considering Residents' comfort

5.2.3 Autumn

For autumn, the charging and discharging power of ESS without and with EV are shown in Fig 5.22 and 5.23 respectively. The results of total cost incurred with ESS and EV are shown in Fig 5.24 and 5.25. The cost of each case is shown in Fig 5.26.

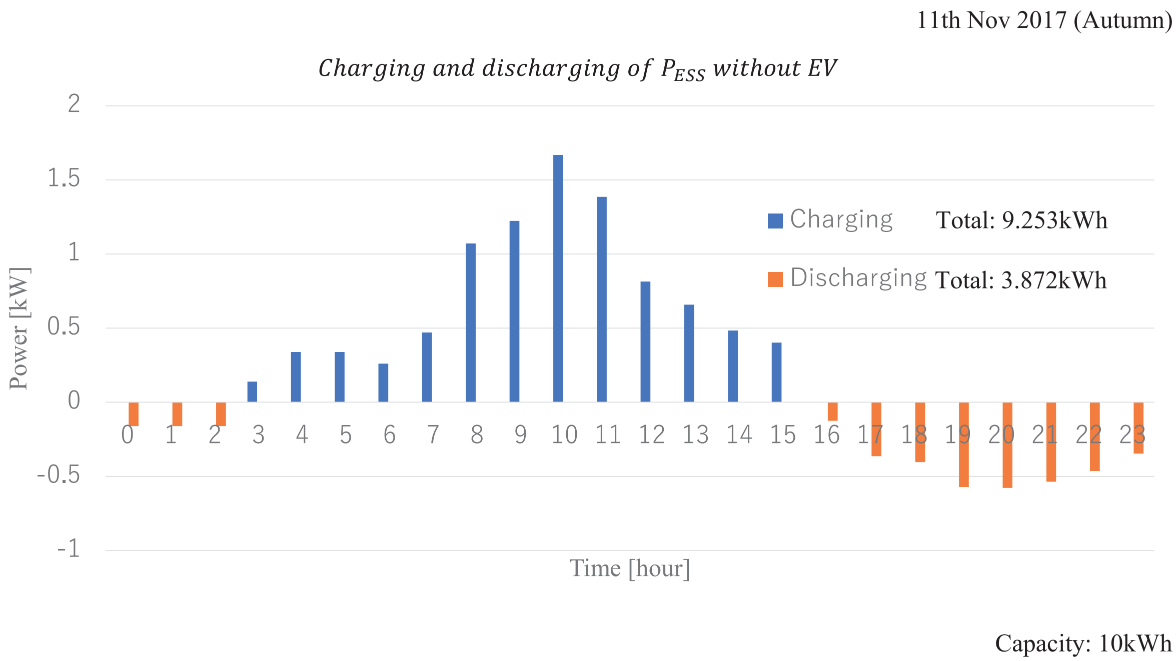

Figure 5.22: Charging and discharging power of ESS without EV in autumn

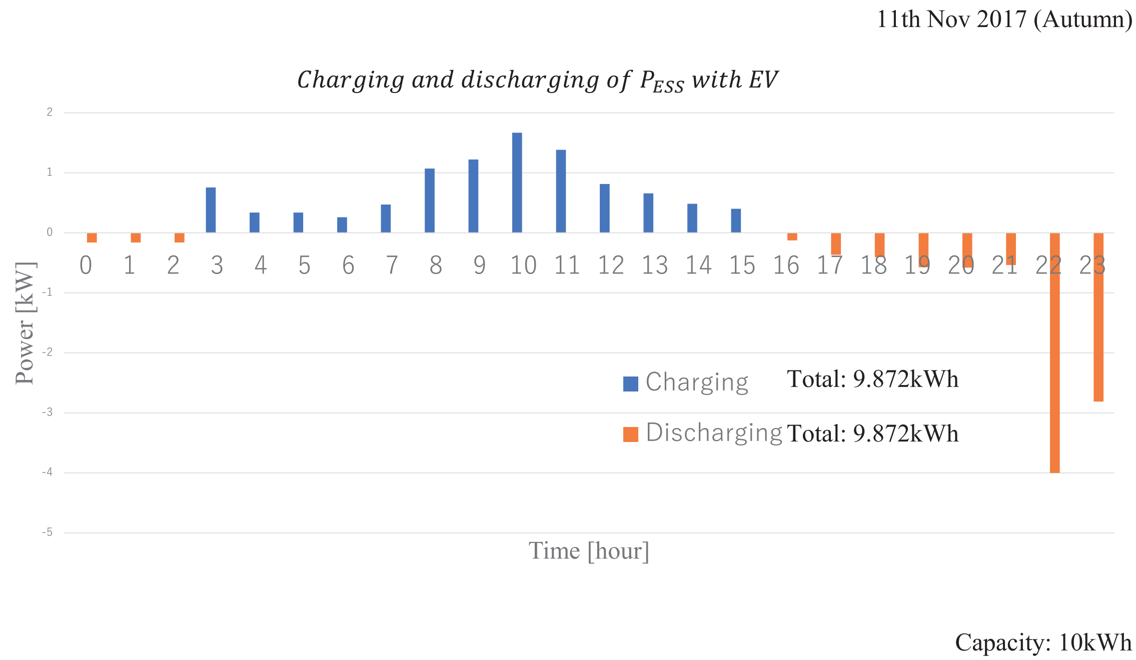

Figure 5.23: Charging and discharging power of ESS with EV in autumn

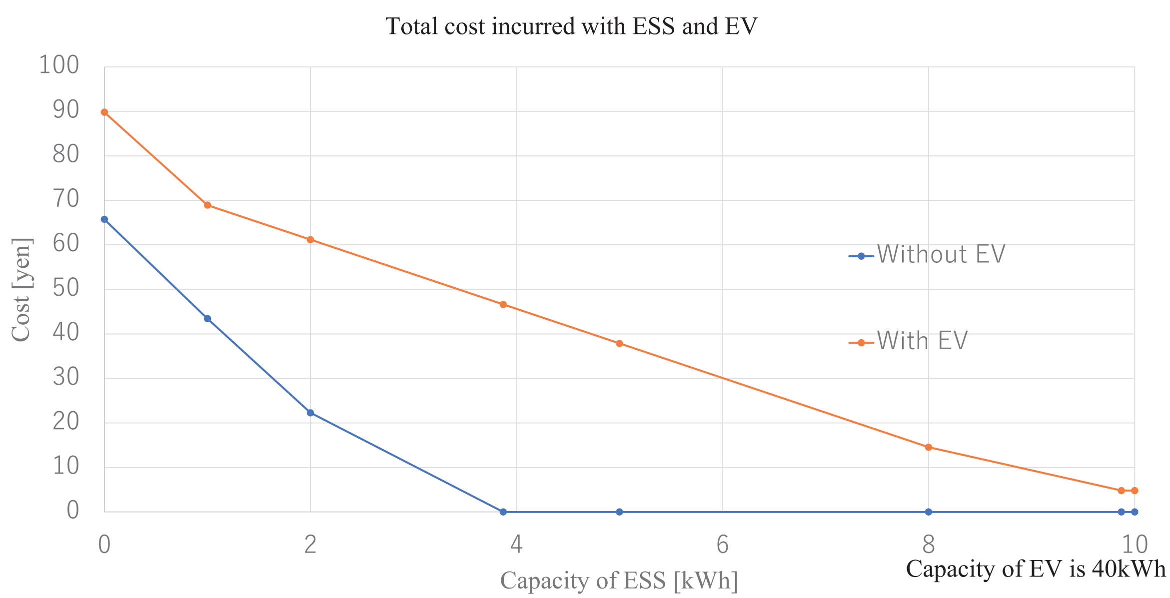

Figure 5.24: Total cost incurred with ESS and EV a

5.2.4 Winter

- Without Considering Residents' Comfort

Figure 5.25: Total cost incurred with ESS and EV b

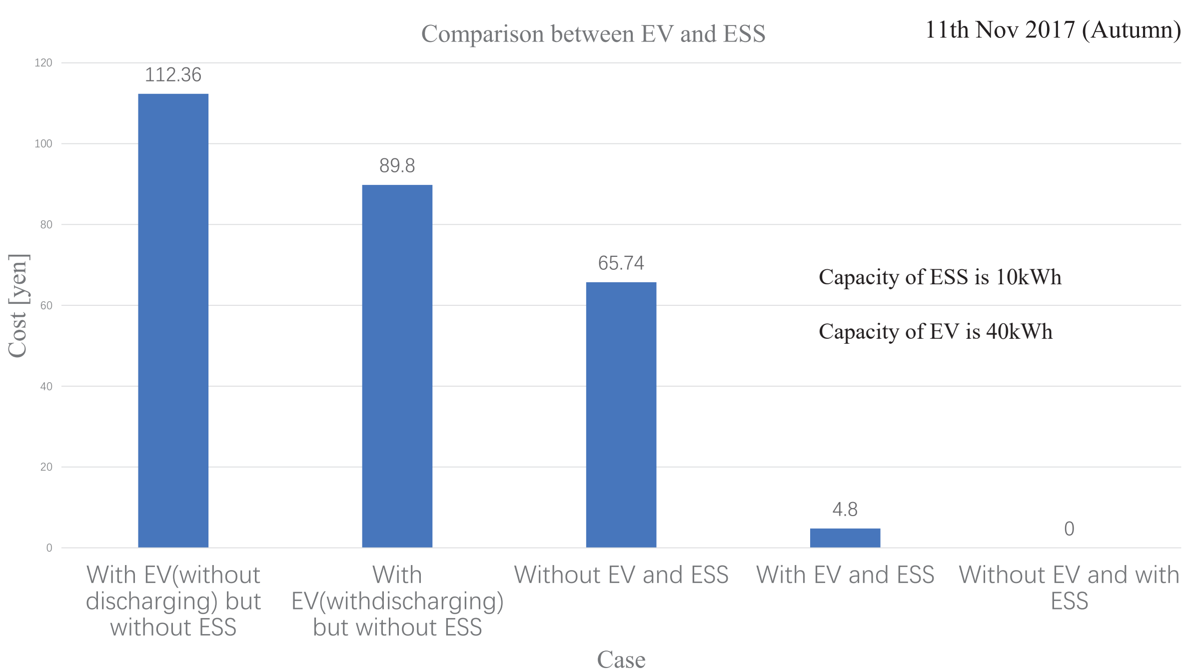

Figure 5.26: Comparison between EV and ESS

For this case, the charging and discharging power of ESS without and with EV are shown in Fig 5.27 and 5.28 respectively. The results of total cost incurred with ESS and EV are shown in Fig 5.29 and 5.30. The cost of each case is shown in Fig 5.31.

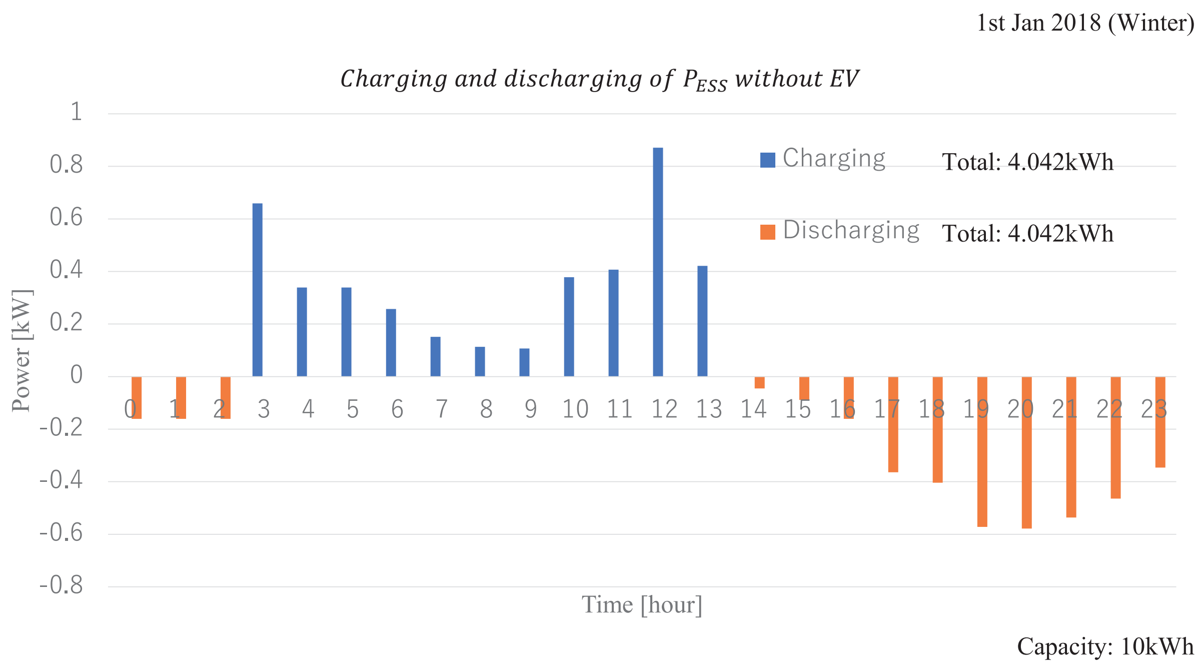

Figure 5.27: Charging and discharging power of ESS without EV in winter

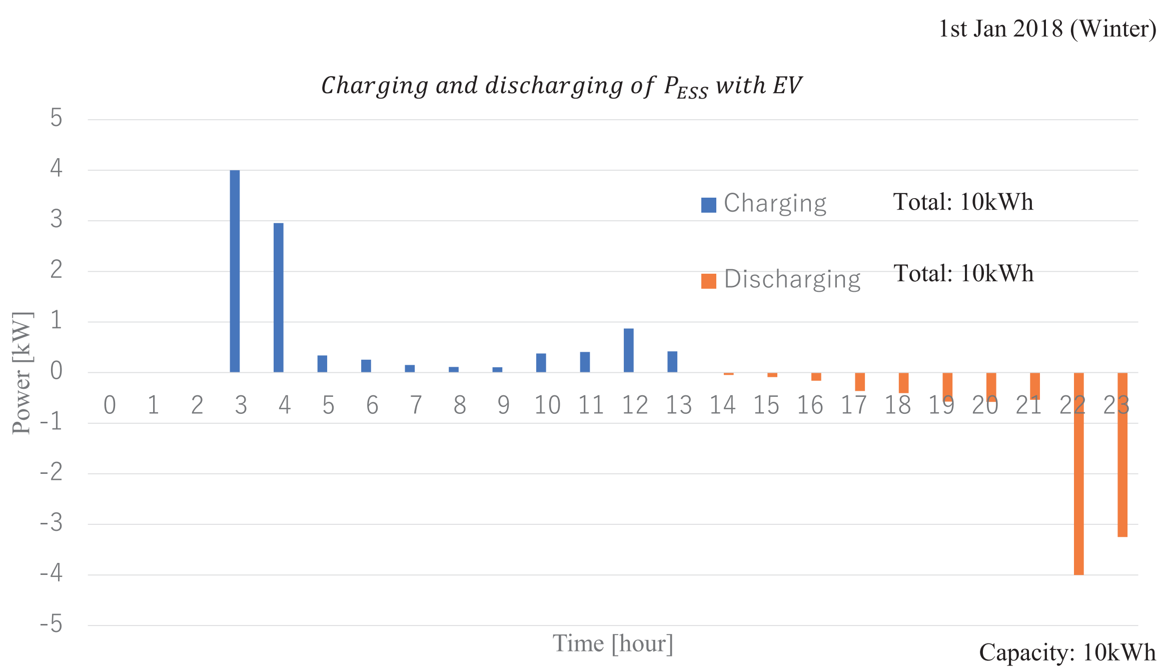

Figure 5.28: Charging and discharging power of ESS with EV in winter

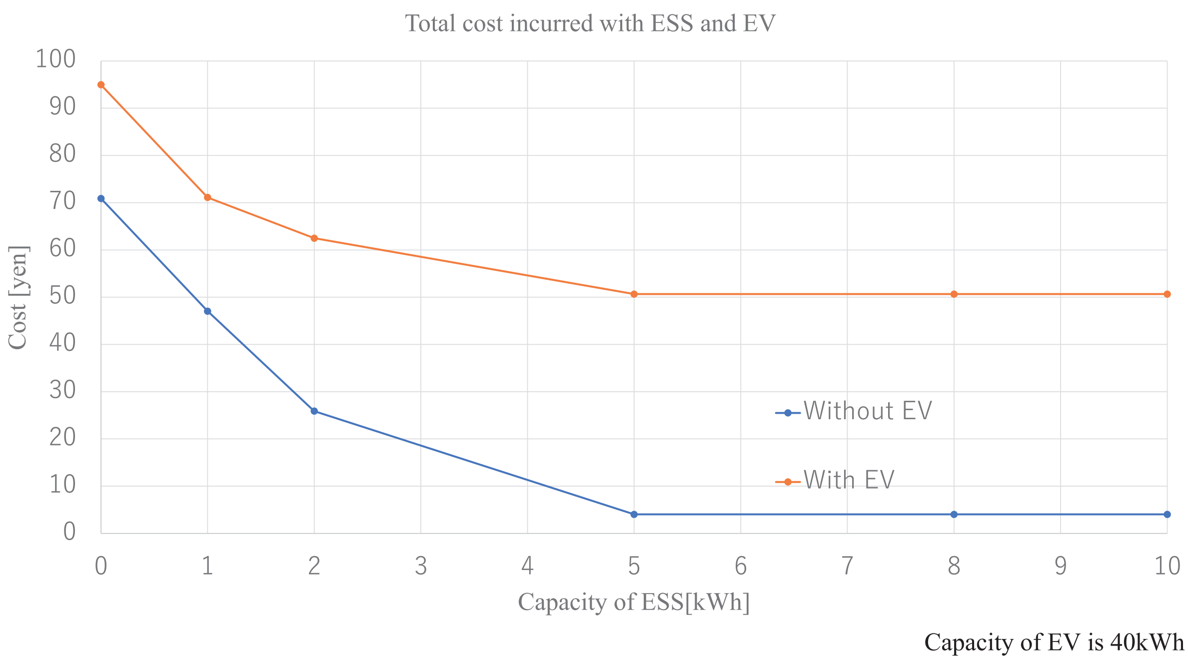

Figure 5.29: Total cost incurred with ESS and EV a

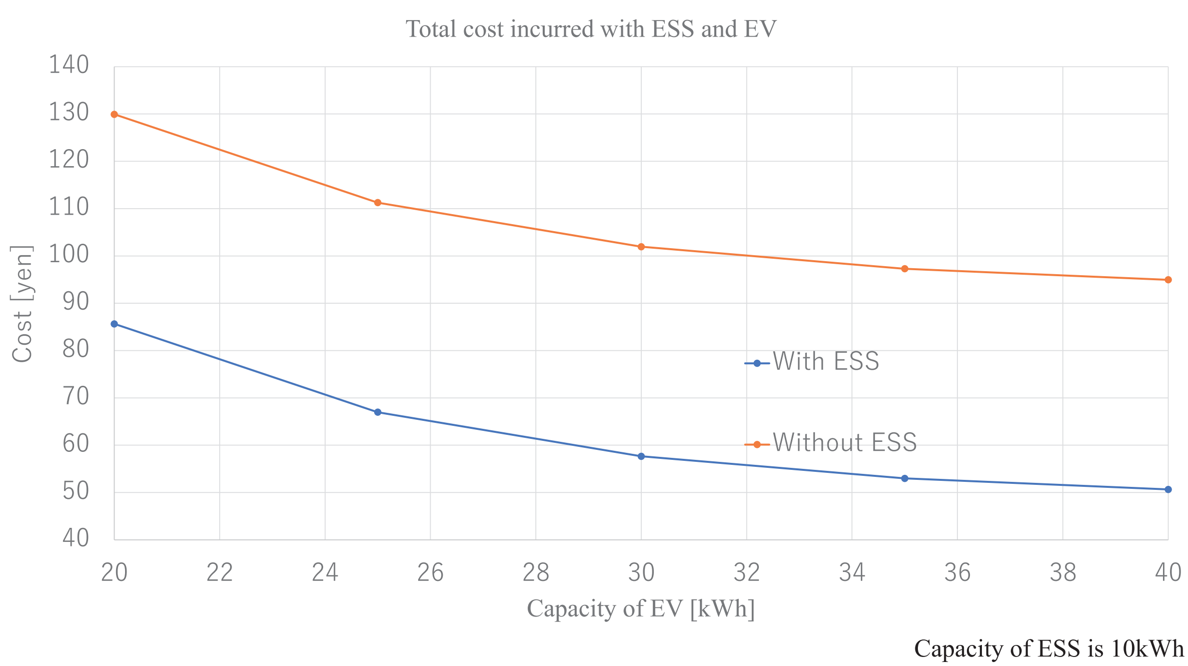

Figure 5.30: Total cost incurred with ESS and EV b

- Considering Residents' Comfort (20°C)

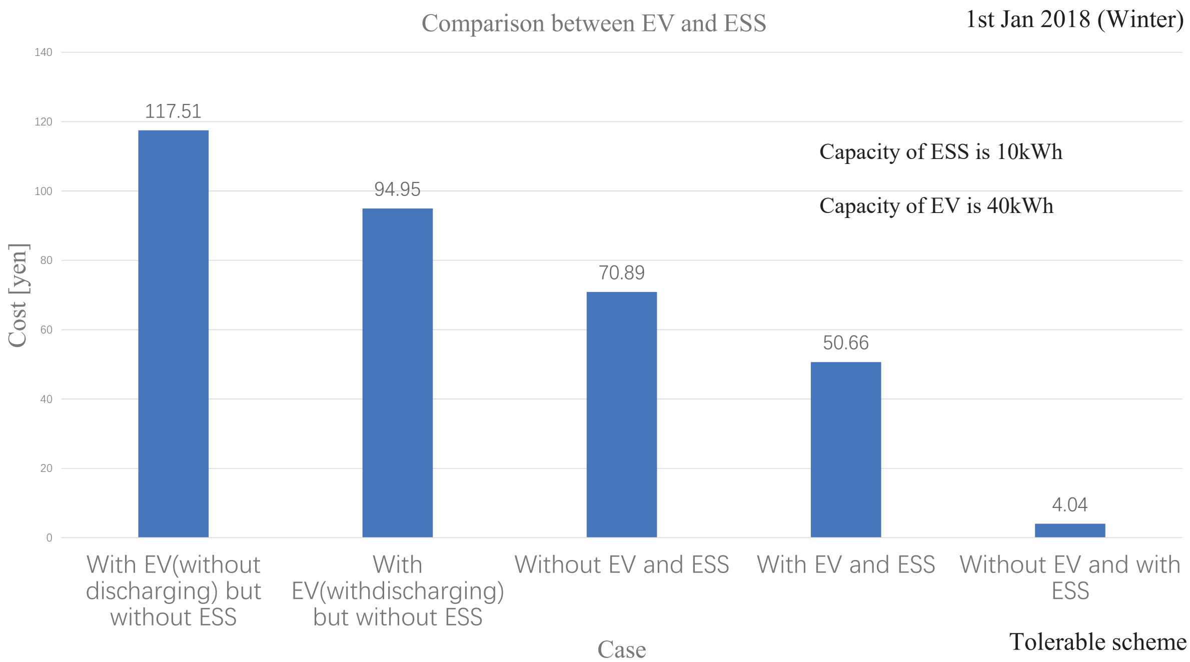

Figure 5.31: Comparison between EV and ESS

For this case, the charging and discharging power of ESS without and with EV are shown in Fig 5.32 and 5.33 respectively. The results of total cost incurred with ESS and EV are shown in Fig 5.34 and 5.35. The cost of each case is shown in Fig 5.36.

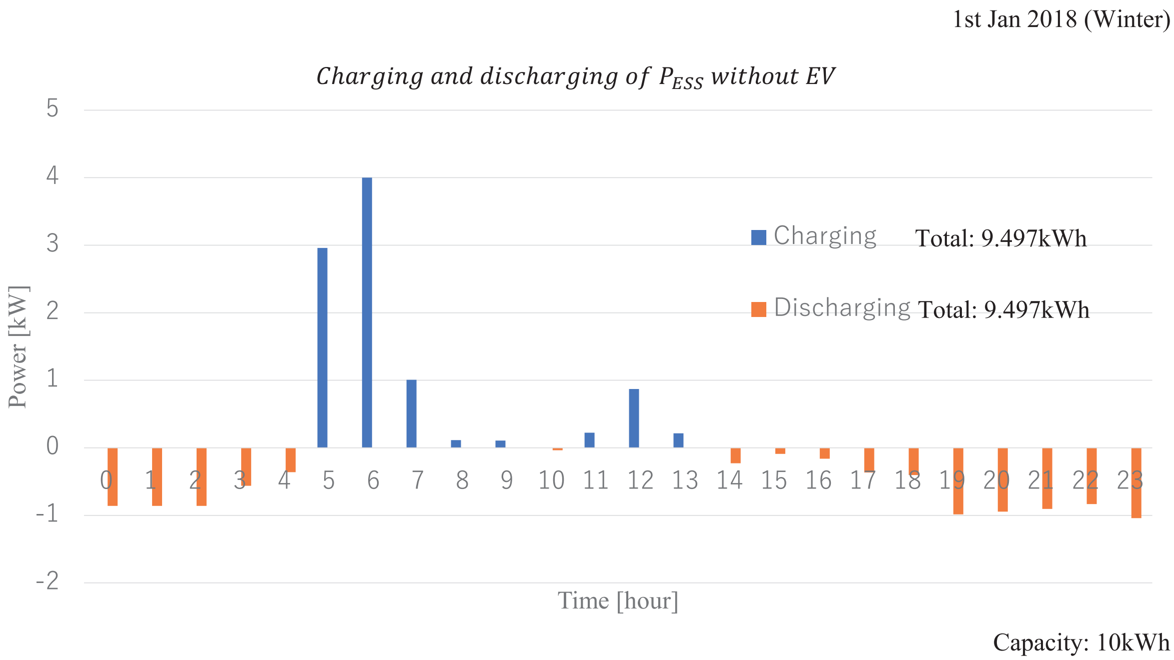

Figure 5.32: Charging and discharging power of ESS without EV in winter

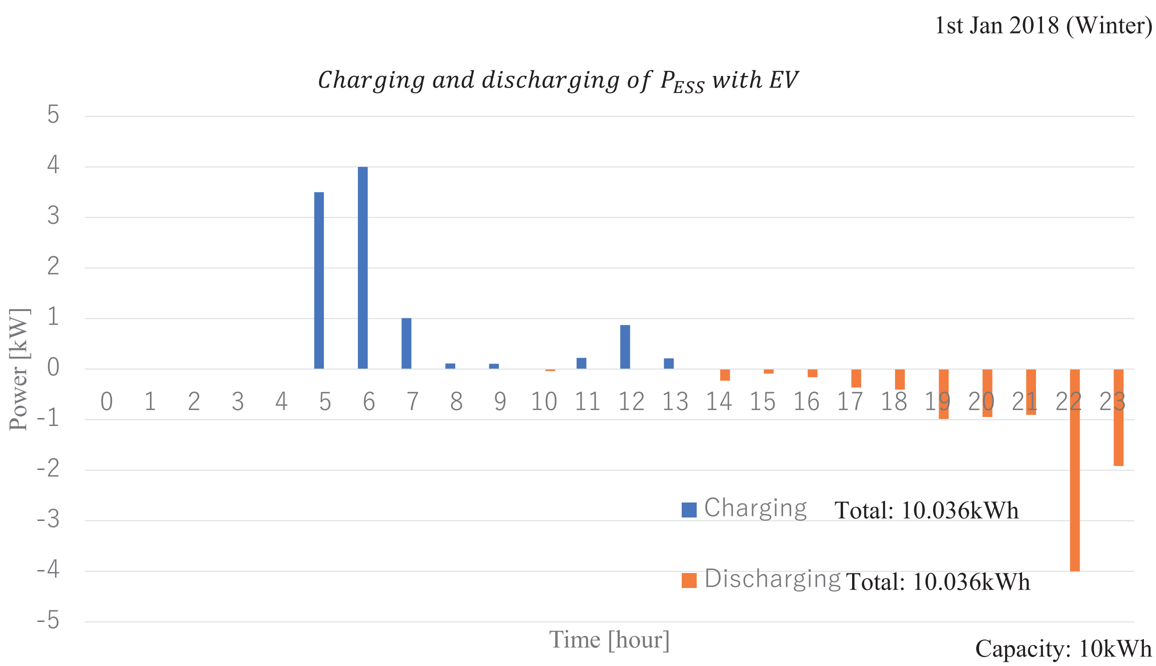

Figure 5.33: Charging and discharging power of ESS with EV in winter

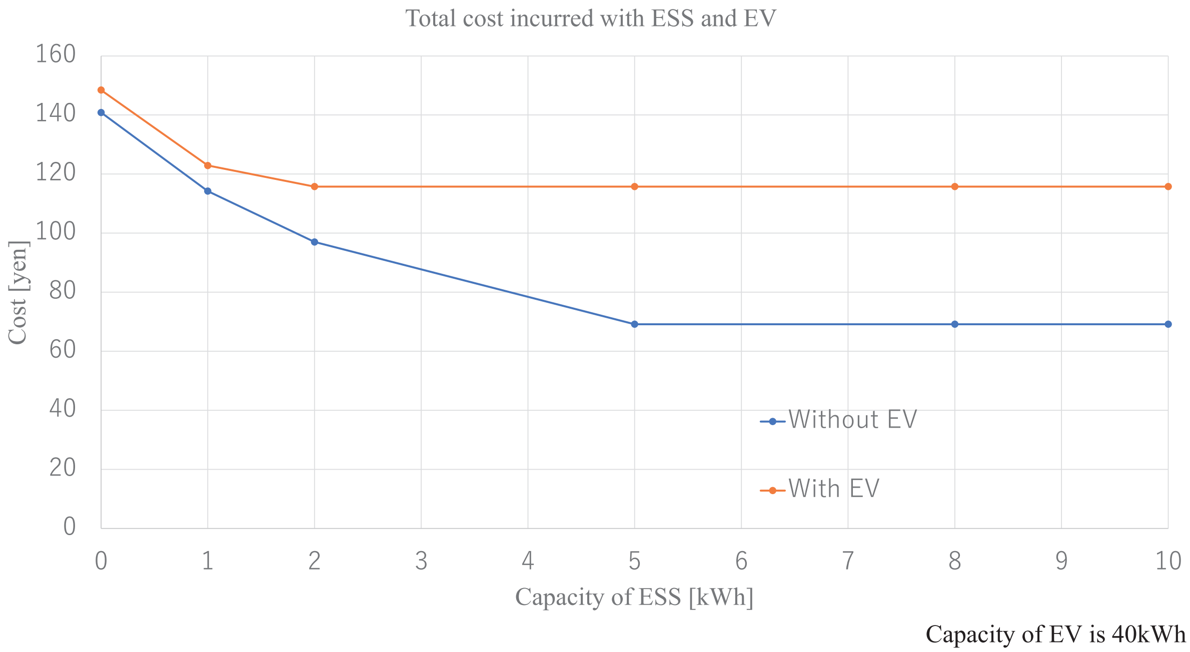

Figure 5.34: Total cost incurred with ESS and EV a

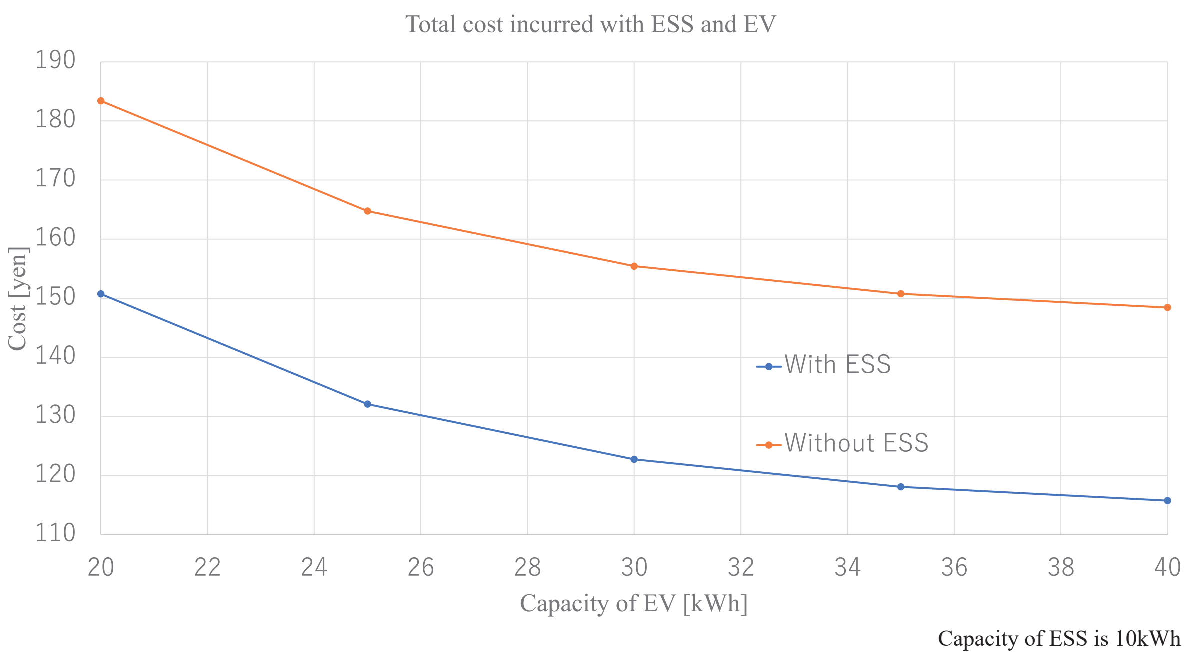

Figure 5.35: Total cost incurred with ESS and EV b

- Considering Residents' Comfort (19°C -21°C)

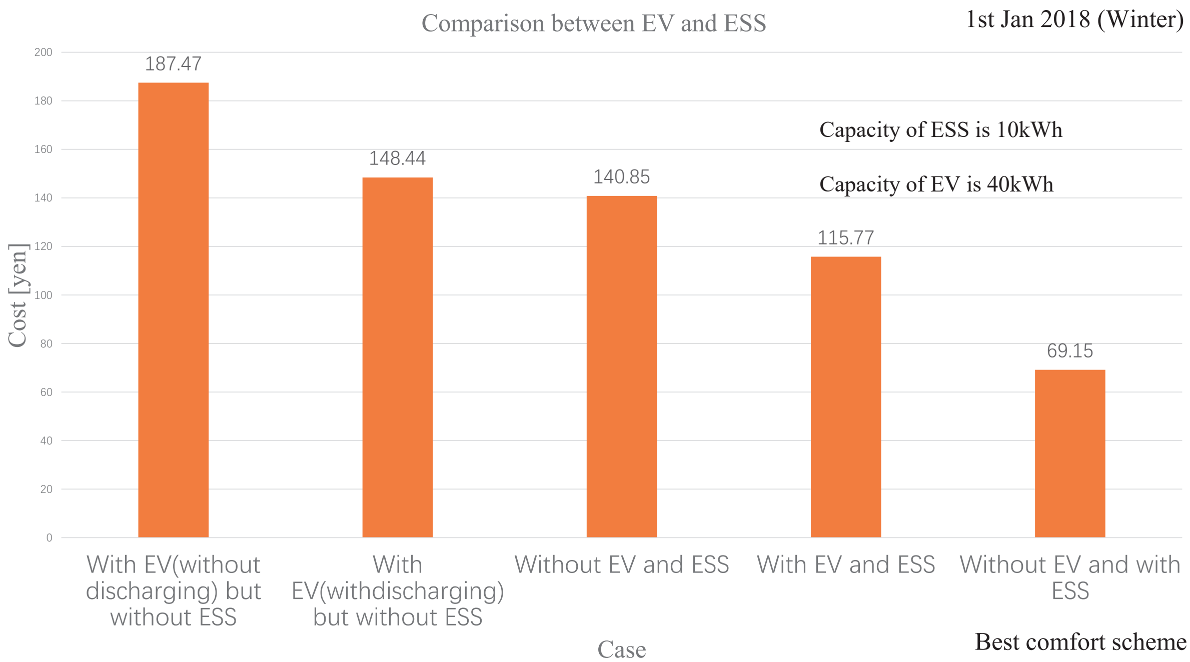

Figure 5.36: Comparison between EV and ESS

For this case, the charging and discharging power of ESS without and with EV are shown in Fig 5.37 and 5.38 respectively. The results of total cost incurred with ESS and EV are shown in Fig 5.39 and 5.40. The cost of each case is shown in Fig 5.41.

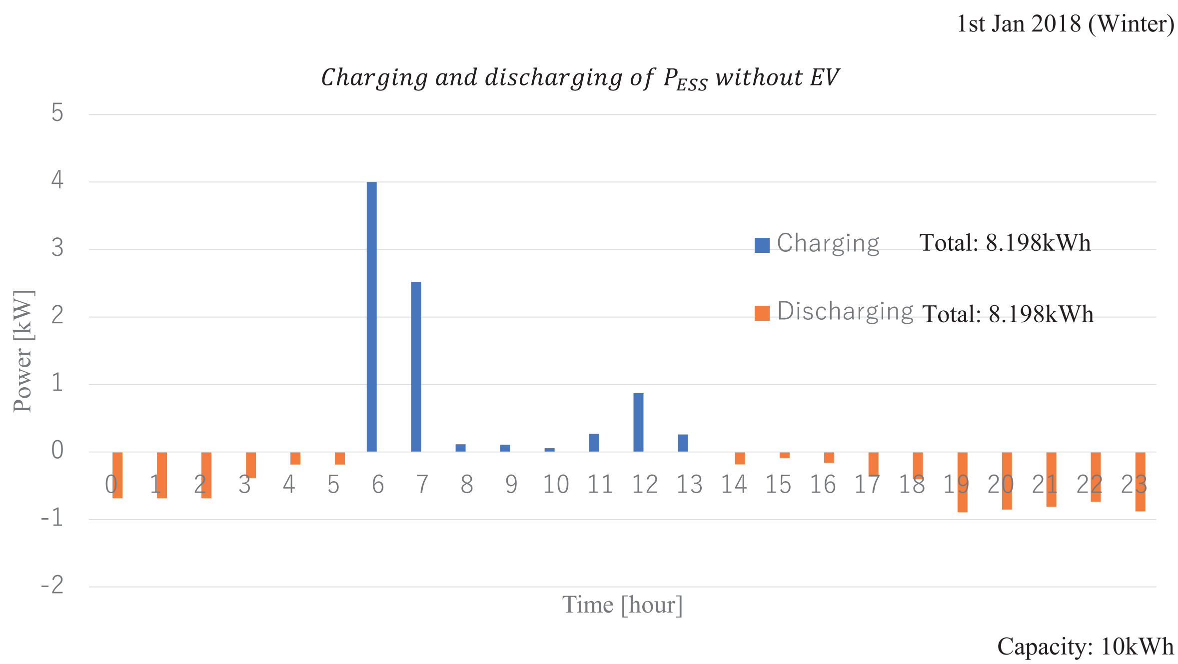

Figure 5.37: Charging and discharging power of ESS without EV in winter

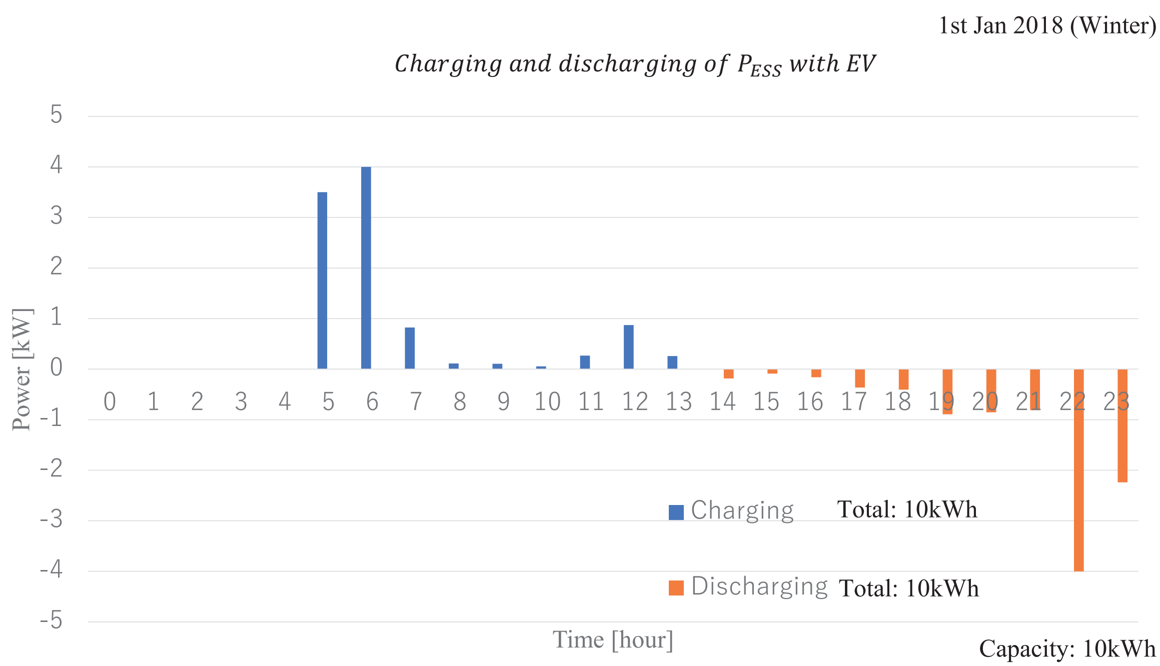

Figure 5.38: Charging and discharging power of ESS with EV in winter

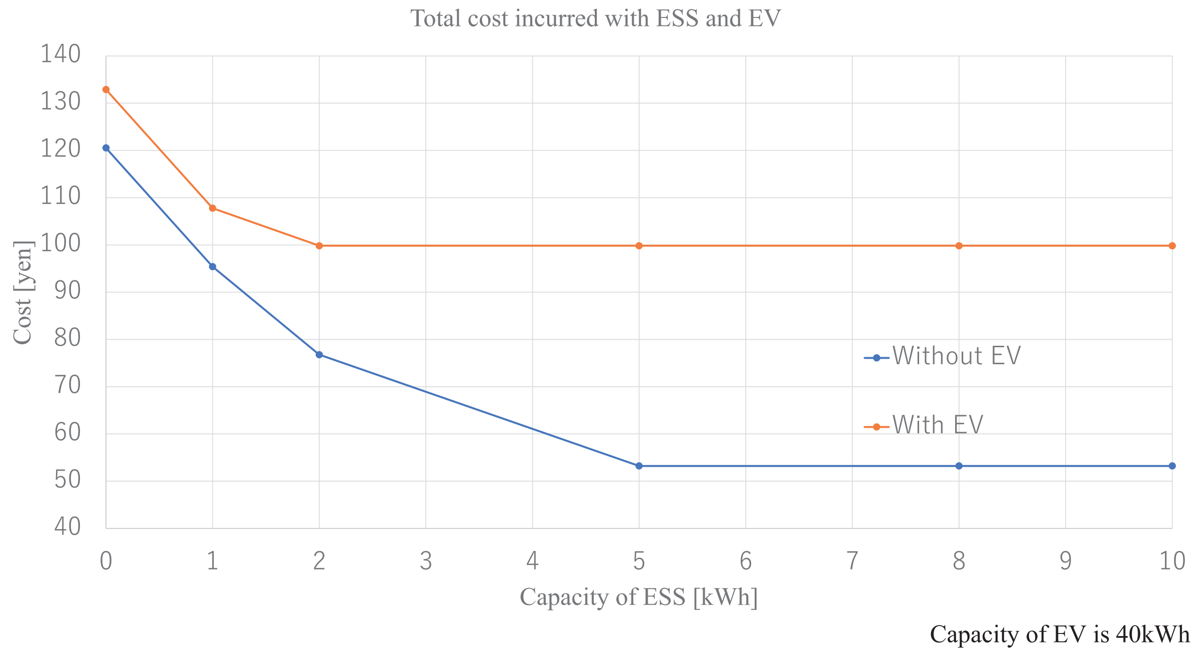

Figure 5.39: Total cost incurred with ESS and EV a

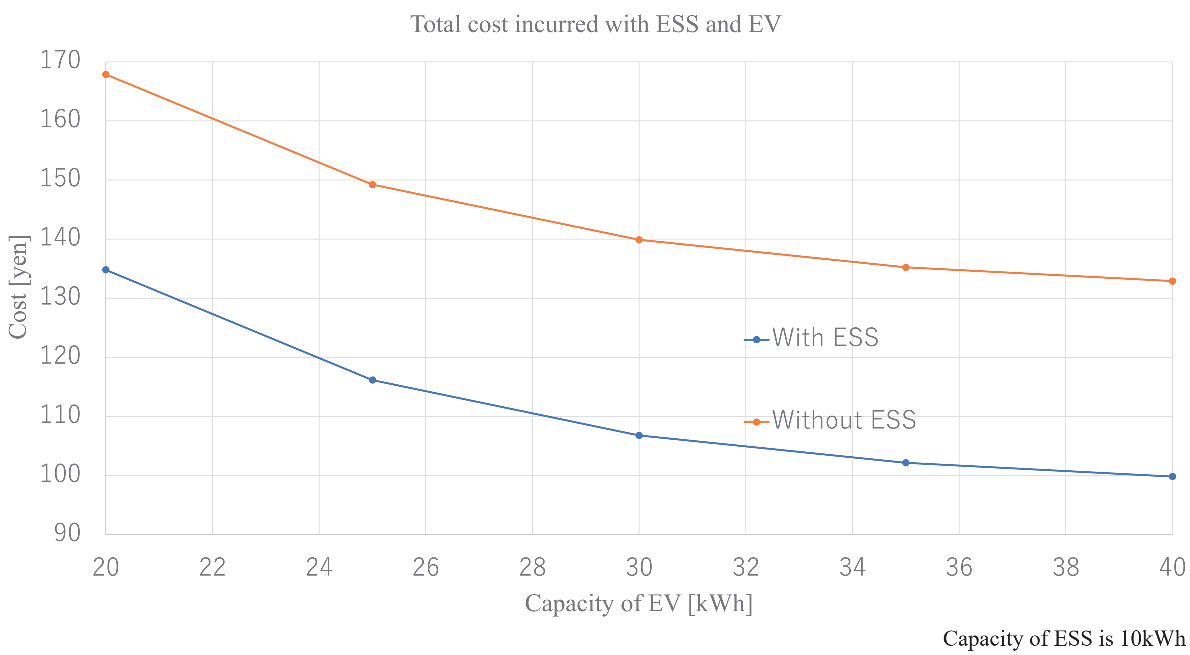

Figure 5.40: Total cost incurred with ESS and EV b

The cost comparison is shown in Fig 5.42

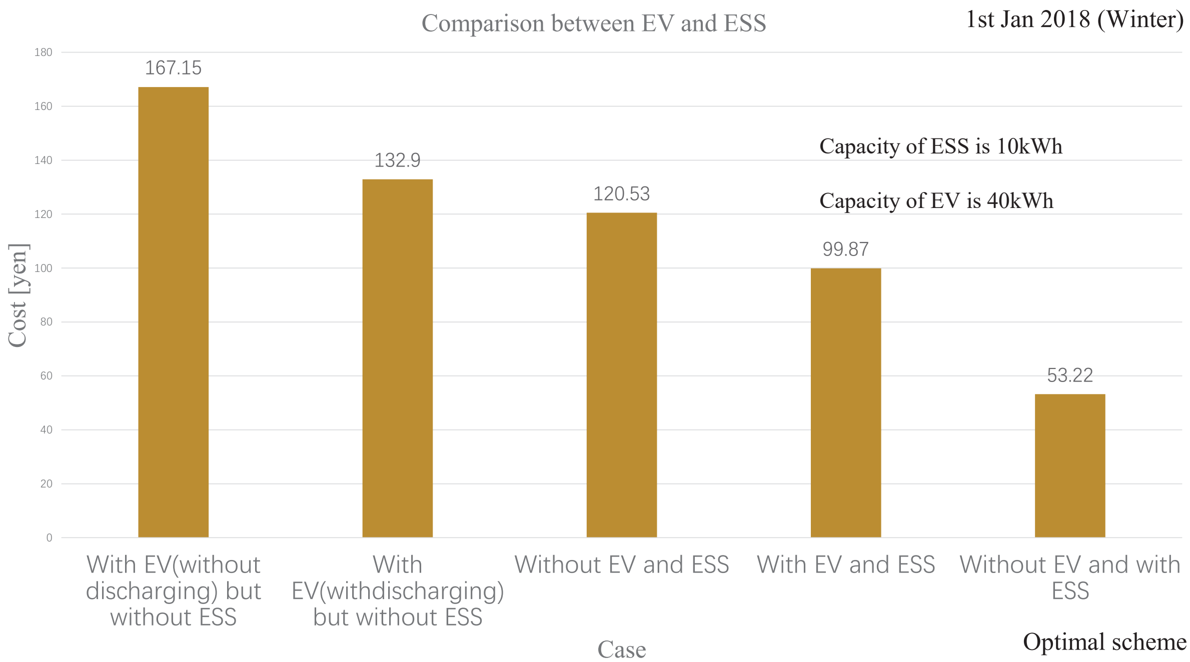

Figure 5.41: Comparison between EV and ESS

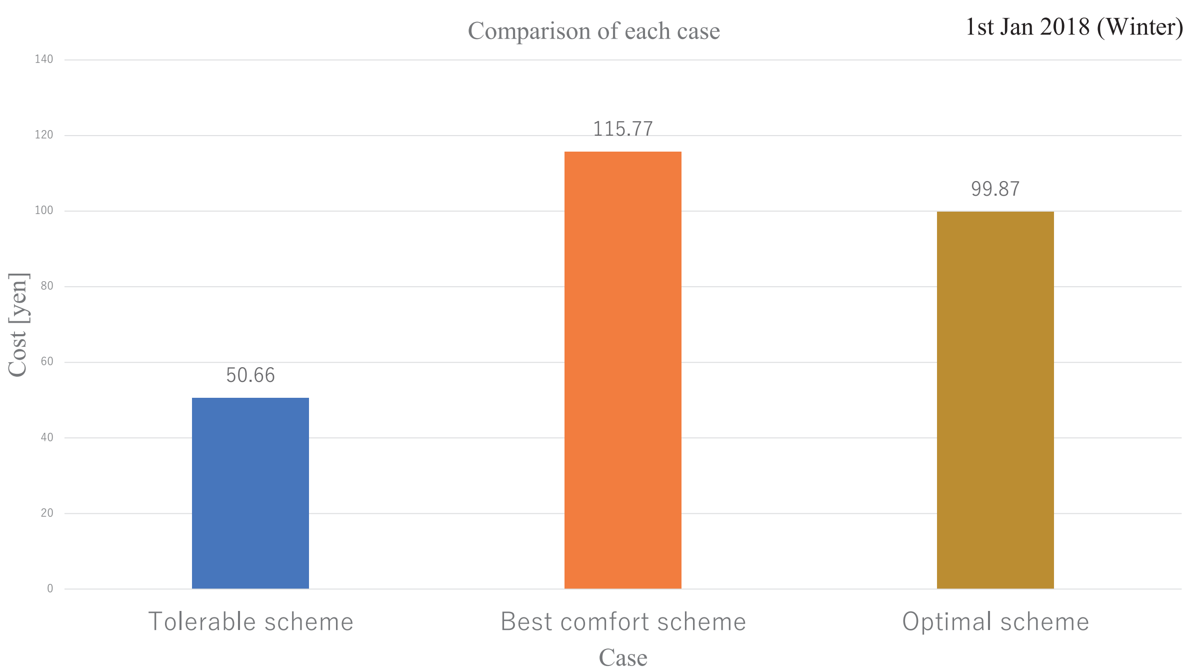

Figure 5.42: Comparison between considering Residents' comfort and without considering Residents' comfort

5.3 Analysis

Form the results we can see, it produce the most energies in the summer and least energies in winter.The PV and FC generation in summmer is enough to meet the demand of EV and other home appliances except HVAC system, so the cost is 0 yen under the case of without considering residents' comfort. If the residents' comfort is considered in summer, cost will increase to 9.59 yen but if the temperature is in a range of $20°C$ to $22°C$, it will save about 33.58%.

For winter, due to the low generation of PV and high demand of HVAC system, it needs ESS and EV to keep energy when the electric price is low in the night in order to provide extra energy when the generation of PV is not enough, it can save about 17% considering residents' comfort and about 28.5% considering residents' comfort.

For autumn and spring, the generation of PV an FC can barely meet the demand. So, it also needs ESS and EV to keep energy.

Chapter 6

Conclusions and Recommendations

In this chapter, I conclude my research done in this thesis and the scheme I proposed can save cost while considering residents' comfort when EV is connected to smart home. It will also let other researchers to further research the situation of multiple-household in a community and schedule other home appliances based on the proposed scheme.

6.1 Concluding Remarks

In this thesis, I do a study of charging and discharging scheme of EV for smart homes. In the first chapter, I introduced the development of EV, which is the trend of near future. The objective of this research is to propose a joint optimization scheme for smart homes which can save cost as well as consider residents' comfort. Thus, the smart community simulator is necessary to analyze the daily consumption, residents' activities, the generation of PV and FC. The driving patterns of EV is also necessary.

Chapter 2 presents the introduction about smart home by defining smart home, discussing the components of smart home. In addition, with the development of EV, EV and V2H system are also introduced in this chapter.

Chapter 3 discusses the experiment environment. After the introductions of iHouse and smart community simulator, the models of renewable energy source, residents' activities, EV and home appliances are built.

Chapter 4 presents the objective functions and the constrain conditions. Based on the data of temperature and the PV, FC generation of iHouse, the charging and discharging scheme is proposed.

Chapter 5 uses the numerical results of the scheme to analyze the necessity of ESS, EV. It will also let other researchers to further research the situation of multiple-household in a community and schedule other home appliances based on the proposed scheme.

Chapter 6 summarizes the works in this paper, draws contributions of ESS, EV and mentions the future work.

6.2 Future Works

- Only the situation of a single household is studied. It is difficult to determine the impact of the optimization scheme proposed in this research after expending to multiple-household in a city community.

- Only the HVAC system is studied in this research. It can add more controllable loads such as dishwasher, cloth washer , cloth dryer ,which have a greater impact on the scheduling of home appliances.

- This research only analyzes a typical driving pattern of electric vehicle. But in actual situations, it may be more complicated.

- The daily electric price can be actual like real-time price which is being researched [31], [32].

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