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Study on Sharing Electricity using Photovoltaic Panels and Storage Batteries in Housing Complexes

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ABSTRACT

After the Great East Japan Earthquake, the household sector of public welfare is promoting the introduction of distributed energy systems by diversifying energy sources and applying local energy use as one of the energy supply measures in case of a disaster. This study introduced an energy-sharing system in the housing complexes to examine whether each house with different family composition and life patterns (i.e., different energy use patterns) could use energy more efficiently. The target energy in the housing complexes was set to electricity, which was generated by photovoltaic panels and stored in storage batteries. The strategy for stable electricity supply and profit generation was as follows: (1) electricity generated by photovoltaic panels is consumed first in the housing complexes; (2) the remaining electricity is stored in a large-capacity storage battery for the operation of the cooling and heating system; (3) afterward, electricity is sold directly to nearby housing complexes at a lower price than the supply price of electricity companies and at a higher price than when sold to electricity companies. The calculation results show that the profit from the sale of surplus electricity and the reduction rate of CO_2 emissions were evaluated. The annual electricity purchase was 87 MWh, which decreased by 52% due to the introduction of the electricity-sharing system. Annual electricity sales were 433 MWh. The annual profit from selling surplus electricity directly to nearby houses was 1.14 times higher than selling to electricity companies. The CO_2 emission reduction rate was 56.2%.

Keywords: Economic evaluation, electricity, electricity sharing system, environmental evaluation, photovoltaic

INTRODUCTION

In Japan, one-third of total CO_2 emissions come from construction-related fields. In addition, the largest share of CO_2 emissions

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in the construction-related sector is due to the energy used in operating the house, which accounts for approximately 40% (Ministry of Land, Infrastructure Japan, 2012). Figure 1 shows a breakdown of house energy sources (Ministry of Economy, Trade and Industry Japan, 2020).

Electricity accounts for more than half (51%) of the energy sources used in houses. It is necessary to consider how to effectively use and reduce electricity, as reducing it in the housing sector can lead to reducing CO_2 emissions in construction-related sectors.

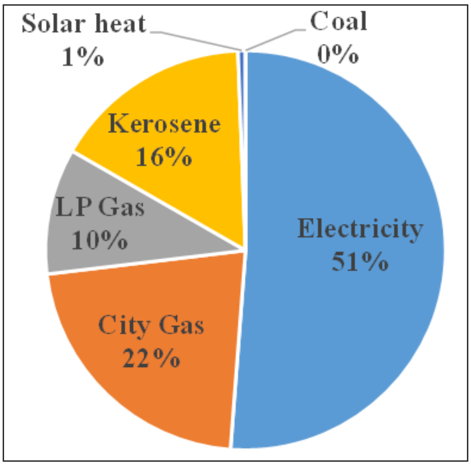


Figure 1. Breakdown of energy sources used in houses in Japan. Electricity accounts for more than half of the energy sources used

Meanwhile, in Korea, Concerns about nuclear accidents are growing due to the wake of the Great East Japan Earthquake in 2011 and a number of recent earthquakes around nuclear power plants. The announcement of the 8th Basic Plan for Electricity Supply and Demand in 2018 accelerates the phase-out of nuclear power and the transition to renewable energy (Nam, 2020). According to statistics from Korea Power Exchange, about 13% of the capacity of domestic electricity generation facilities is renewable energy-related facilities, including photovoltaic panels, of which photovoltaic power generation accounts for about 67% (Korea Power Exchange, 2019).

Investigation into smart city development began in the early 2000s, and the number of projects steadily increases every year. In 2018, the government set smart city development as one of the national development strategies; in 2018, 78 development projects were in progress (Lee, 2019). The key to energy in a smart city is renewable energy and transitioning to a low-carbon society. Renewable energy is produced, stored, distributed, and consumed in the smart grid (Lim et al., 2019). Most of the renewable energy used in smart cities is solar power generation. It is necessary to review technologies and strategies for efficient storage and distribution as well as the production of electricity through photovoltaic generation.

Daily Electrical Energy Balance in a House

Laws on energy conservation have recently been reorganized to strengthen insulation and airtightness performance as part of efforts to reduce CO_2 emissions in construction-related fields. In addition, the use of natural energy is being actively prospected. In particular, research in the housing sector is being conducted on developing energy-saving housing. The number of photovoltaic power generation facilities installed in houses has increased substantially, and according to data from the Japan Photovoltaic Energy Association, the installation rate of photovoltaic power generation facilities in houses rose to 9% as of 2019, with an increase of 0.7% from 8.3% in the previous year 2018 (Solar Power Association Japan, 2020). The number of installations is expected to continue to increase.

This study examines the livelihood of efficient electric energy by considering the balance between electricity consumption and electricity generation in houses with photovoltaic panels. Figure 2 shows a conceptual diagram of the change in a house's daily electricity consumption (Iwata et al., 2012). Figure 3 is a conceptual diagram showing electric energy generation in a house equipped with photovoltaic panels. As shown in Figure 2, energy consumption in the house is concentrated in the morning hours, when one prepares to go to work or school, and in the evening to night hours, when family members return home. Conversely, as shown in Figure 3, photovoltaic power generation gradually increases from sunrise in proportion to the horizontal total solar radiation and is the largest at noon. Afterward, it reduces again until sunset. In other words, a gap exists between when electricity consumption is large and when photovoltaic power generation is large; therefore, the per-hour supply and demand of electricity are not balanced. It is thus necessary to balance the supply and demand of electricity to efficiently use electricity generated by photovoltaic panels without waste and avoid unnecessary thermal power generation. To this end, a method of storing electricity generated during the day in a storage battery and using it in a time zone when electricity demand is high may be considered.

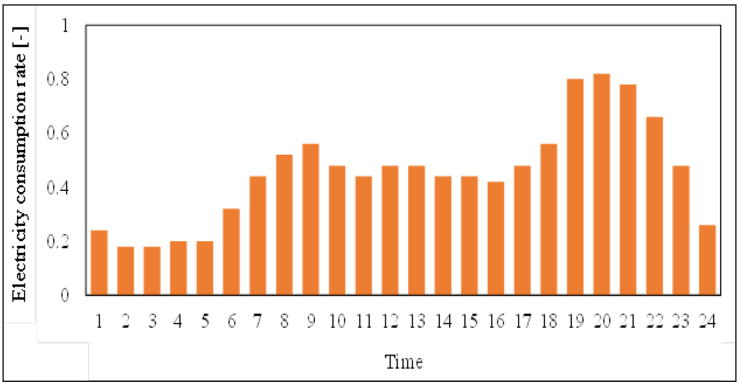


Figure 2. Conceptual diagram of the change in a house's daily electricity consumption. Energy consumption in the house is concentrated in the morning hours and in the evening to night hours

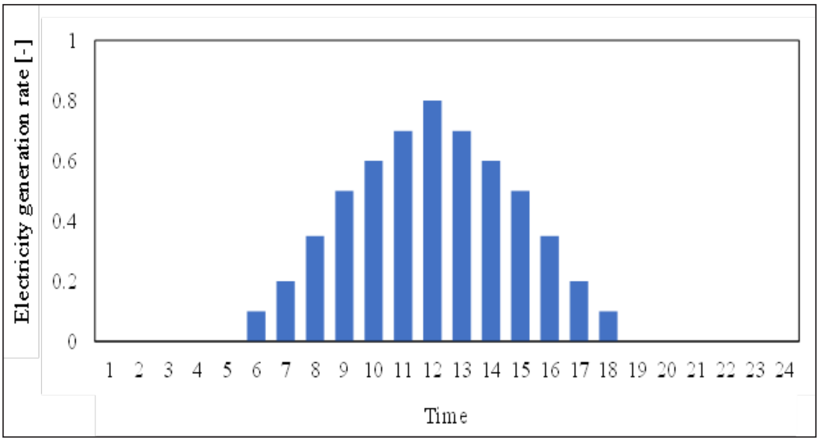


Figure 3. Conceptual diagram of the change in daily electricity generation. photovoltaic power generation is the largest at noon

Advantages of Electricity Sharing in a Housing Complex

In the wake of the Great East Japan Earthquake in 2011, the introduction of the distributed energy system has been considered and area-energy-using promoted as part of energy management measures in the residential sector (Akisawa & Takeshita, 2016; Kutsuki et al., 2008; Yuasa et al., 2007, 2020). This study introduces a photovoltaic power generation system in housing complexes as a distributed energy system. It investigates whether power generation and electricity consumption are possible considering the housing complexes' balance of supply and demand.

In the case of photovoltaic power generation on a house basis, when the amount of electricity consumption required is greater than that of electricity, the shortfall must be purchased from electricity companies. Conversely, when housing complexes are targeted, some houses have high electricity demand and others low due to differences in living patterns, even at the same time. Managing electrical energy for electricity demand throughout the housing complex can achieve the leveling of electricity demand by offsetting shortages and surpluses. Therefore, electricity can be used stably without additional electricity purchases from power companies.

Although photovoltaic panels are usually installed on roofs in individual houses, in the housing complexes, they can be installed not only on roofs but also in public areas such as passages, parking lots, and community centers, increasing the amount of electricity generation. In addition, it is unnecessary to install storage batteries with large capacity in individual houses as they are installed as common facilities.

Another benefit is that renewable energy, which is difficult to utilize in individual buildings due to the low economic feasibility of the return on investment, can be effectively used as an energy source, thereby reducing environmental load. Compared to the past, it is difficult to profit from the sale of surplus electricity due to the fall in the selling price of electricity sold to electricity companies (Ministry of Economy Trade and Industry Japan, 2021). In this study, surplus electricity is sold directly to nearby houses at a higher price than when selling electricity to electricity companies to make a higher profit from surplus electricity sales. In addition, the purchaser of surplus electricity is set up to purchase electricity at a lower price than when buying it from electricity companies. It is beneficial to both the seller and purchaser of surplus power.

METHODS

Target Housing Complexes and Analysis Tool

This study conducted numerical analysis on housing complexes in Busan, Korea, as shown in Figure 4. The complex consists of 56 houses of 13 types, including a community center.

The study investigated whether high and low electricity consumption could be offset by sharing electricity in the housing complexes. Electricity consumption and internal heat generation vary depending on family composition and lifestyle patterns. In this regard, all target households in the housing complexes were set up as a family of four. Each family member was designed by types A, B, and C. Type A consisted of a working husband, a full-time housewife, and two elementary school children. Type B consisted of a working husband, a full-time housewife, and two high school children. Type C consisted of a working husband, a full-time housewife, and two children of a worker. Tables 1–6 show occupant and internal heating schedules for types A, B, and C. In addition, Tables 7–12 are the cooling and heating schedules for each room of three types.

A numerical analysis using TRNSYS was conducted on the cooling and heating loads of each house in the housing complexes, electricity consumption, photovoltaic power generation, storage and discharge of storage batteries, purchase and sale of electricity, underground heat exchange, underground heat pump, hot-water heat pump, thermal energy storage tank, and heat exchanger. TRNSY is analysis software with an expandable and compatible module structure, allowing users to build systems and perform simulations according to their purposes (The University Wisconsin Madison, n.d.). Figure 5 shows the setting screen on TRNSYS. A calculates the photovoltaic power generation according to the photovoltaic panel's type, tilt angle, orientation, and total horizontal solar radiation. In contrast, B and C analyze heat pumps, thermal energy storage tanks, and heat exchangers for cooling, heating, and hot water supply. The heat source for cooling and heating and hot-water supply is set as the underground heat of E. The storage and discharge of electricity, surplus electricity, electricity sales, and electricity purchases were calculated at D by considering electricity consumption in each house, photovoltaic power generation at A, and electricity consumption for cooling and heating hot-water supply at B and C. The previous analysis estimated the electricity consumption of E, B, and C, and this article reports the results of A and D using the previous analysis results.

Figure 4. Target housing complex and arrangement of photovoltaic panels

Economic evaluations were performed on electricity purchases from electricity companies and surplus electricity sales, and environmental evaluations were conducted on the reduction of electricity purchases from electricity companies due to photovoltaic power generation and the resulting reduction in the amount of fossil fuels required for electricity generation.

Table 13 shows the heat transfer coefficient (U-value) of external walls, internal walls, floors, interlayer slabs, roofs, doors, and windows. The target housing complexes' insulation performance level is too high for energy conservation.

Table 1
Internal heat generation schedule of Type A (weekdays)

Zone	Heat gain	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	0:00
Living Room	Human body [W]	0	0	0	0	0	0	0	0	0	100	100	100	0	0	100	100	0	150	0	175	250	250	200	0
	Lighting [W]	4	4	4	4	4	4	40	40	40	40	4	4	4	4	4	4	4	40	40	40	40	40	40	4
	TV [W]	16	16	16	16	16	16	162	162	162	162	162	162	162	16	16	16	16	162	162	162	162	162	162	16
Dining Kitchen	Human body [W]	0	0	0	0	0	0	100	350	0	0	0	0	100	0	0	0	0	100	350	0	0	0	0	0
	Lighting [W]	4	4	4	4	4	4	40	40	40	40	4	4	4	4	4	4	4	40	40	40	40	40	40	4
	IH [W]	12	12	12	12	12	12	400	12	12	12	12	12	12	12	12	12	12	400	12	12	12	12	12	12
	Refrigerator [W]	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11
	Rice cooker [W]	15	15	15	15	15	150	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
Bedroom 1	Human body [W]	200	200	200	200	200	200	100	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	200
	Lighting [W]	4	4	4	4	4	4	40	4	4	4	4	4	4	4	4	4	4	4	4	40	4	4	4	40
	Personal computer [W]	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	30	3	3	3	3
Bedroom 2	Human body [W]	75	75	75	75	75	75	75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	75	75
	Lighting [W]	4	4	4	4	4	4	40	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Bedroom 3	Human body [W]	75	75	75	75	75	75	75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	75	75
	Lighting [W]	4	4	4	4	4	4	40	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Others	Washing machine [W]	14	14	14	14	14	14	14	14	82	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14
	Hair dryer [W]	0	0	0	0	0	0	0	0	82	0	0	0	0	0	0	0	0	0	0	100	100	0	0	0
	Vacuum cleaner [W]	0	0	0	0	0	0	0	0	83	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 2
Internal heat generation schedule of Type A (weekend)

Zone	Heat gain	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	0:00
Living Room	Human body [W]	0	0	0	0	0	0	0	0	0	250	250	250	250	0	0	100	100	100	0	275	250	350	200	0
	Lighting [W]	4	4	4	4	4	4	4	40	40	40	4	4	4	4	4	4	40	40	40	40	40	40	40	4
	TV [W]	16	16	16	16	16	16	16	162	162	162	162	162	162	162	162	162	162	162	162	162	162	162	162	16
Dining Kitchen	Human body [W]	0	0	0	0	0	0	0	100	350	0	0	0	100	350	0	0	0	100	350	0	0	0	0	0
	Lighting [W]	4	4	4	4	4	4	4	40	40	40	4	4	4	4	4	4	40	40	40	40	40	40	40	4
	IH [W]	12	12	12	12	12	12	12	400	12	12	12	12	12	12	12	12	12	400	12	12	12	12	12	12
	Refrigerator [W]	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11
	Rice cooker [W]	15	15	15	15	15	15	150	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
Bedroom 1	Human body [W]	200	200	200	200	200	200	200	100	0	100	100	100	0	0	100	100	100	0	0	0	0	0	0	200
	Lighting [W]	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	40	4	4	4	4	4	4	40
	Personal computer [W]	3	3	3	3	3	3	3	3	3	30	30	30	3	3	3	3	3	3	3	3	3	3	3	3
Bedroom 2	Human body [W]	75	75	75	75	75	75	75	75	0	0	0	0	0	0	75	75	75	75	0	0	0	0	75	75
	Lighting [W]	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	40	40	4	4	4	4	4	4
Bedroom 3	Human body [W]	75	75	75	75	75	75	75	75	0	0	0	0	0	0	75	75	75	75	0	0	0	0	75	75
	Lighting [W]	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	40	40	4	4	4	4	4	4
Others	Washing machine [W]	14	14	14	14	14	14	14	14	14	82	14	14	14	14	14	14	14	14	14	14	14	14	14	14
	Hair dryer [W]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	0	0	0
	Vacuum cleaner [W]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	83	0	0	0	0	0	0	0	0	0

Table 3
Internal heat generation schedule of Type B (weekdays)

Zone	Heat gain	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	0:00
Living Room	Human body [W]	0	0	0	0	0	0	0	0	0	100	100	100	0	0	100	100	0	0	0	300	300	200	200	0
	Lighting [W]	4	4	4	4	4	4	40	40	40	40	4	4	4	4	4	4	4	40	40	40	40	40	40	4
	TV [W]	16	16	16	16	16	16	162	162	162	162	162	162	162	16	16	16	16	162	162	162	162	162	162	16
Dining Kitchen	Human body [W]	0	0	0	0	0	0	100	400	0	0	0	0	100	0	0	0	0	100	400	0	0	0	0	0
	Lighting [W]	4	4	4	4	4	4	40	40	40	40	4	4	4	4	4	4	4	40	40	40	40	40	40	4
	IH [W]	12	12	12	12	12	12	400	12	12	12	12	12	12	12	12	12	12	400	12	12	12	12	12	12
	Refrigerator [W]	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11
	Rice cooker [W]	15	15	15	15	15	150	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
Bedroom 1	Human body [W]	200	200	200	200	200	200	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200
	Lighting [W]	4	4	4	4	4	4	40	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	40
	Personal computer [W]	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	30
Bedroom 2	Human body [W]	100	100	100	100	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100
	Lighting [W]	4	4	4	4	4	4	40	4	4	4	4	4	4	4	4	4	4	4	4	4	4	40	40	40
	Personal computer [W]	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	30	30	3
Bedroom 3	Human body [W]	100	100	100	100	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100
	Lighting [W]	4	4	4	4	4	4	40	4	4	4	4	4	4	4	4	4	4	4	4	4	4	40	40	40
	Personal computer [W]	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	30	30	3
Others	Washing machine [W]	14	14	14	14	14	14	14	14	82	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14
	Hair dryer [W]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	0	0	0
	Vacuum cleaner [W]	0	0	0	0	0	0	0	0	83	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 4
Internal heat generation schedule of Type B (weekend)

Zone	Heat gain	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	0:00
Living Room	Human body [W]	0	0	0	0	0	0	0	0	0	300	300	300	300	0	100	200	200	100	0	300	300	400	400	0
	Lighting [W]	4	4	4	4	4	4	4	40	40	40	4	4	4	4	4	4	40	40	40	40	40	40	40	4
	TV [W]	16	16	16	16	16	16	16	162	162	162	162	162	162	162	162	162	162	162	162	162	162	162	162	16
Dining Kitchen	Human body [W]	0	0	0	0	0	0	0	100	400	0	0	0	100	400	0	0	0	100	400	0	0	0	0	0
	Lighting [W]	4	4	4	4	4	4	4	40	40	40	4	4	4	4	4	4	40	40	40	40	40	40	40	4
	IH [W]	12	12	12	12	12	12	12	400	12	12	12	12	12	12	12	12	12	400	12	12	12	12	12	12
	Refrigerator [W]	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11
	Rice cooker [W]	15	15	15	15	15	15	150	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
Bedroom 1	Human body [W]	200	200	200	200	200	200	200	100	0	100	100	100	0	0	0	0	0	0	0	0	0	0	0	200
	Lighting [W]	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	40
	Personal computer [W]	3	3	3	3	3	3	3	3	3	30	30	30	3	3	3	3	3	3	3	3	3	3	3	3
Bedroom 2	Human body [W]	100	100	100	100	100	100	100	100	0	0	0	0	0	0	100	100	100	100	0	0	0	0	0	100
	Lighting [W]	40	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	40	40	4	4	4	4	4	40
	Personal computer [W]	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	30	30	30	3	3	3	3	3	3
Bedroom 3	Human body [W]	100	100	100	100	100	100	100	100	0	0	0	0	0	0	100	100	100	100	0	0	0	0	0	100
	Lighting [W]	40	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	40	40	4	4	4	4	4	40
	Personal computer [W]	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	30	30	30	3	3	3	3	3	3
Others	Washing machine [W]	14	14	14	14	14	14	14	14	14	82	14	14	14	14	14	14	14	14	14	14	14	14	14	14
	Hair dryer [W]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	0	0	0
	Vacuum cleaner [W]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	83	0	0	0	0	0	0	0	0	0

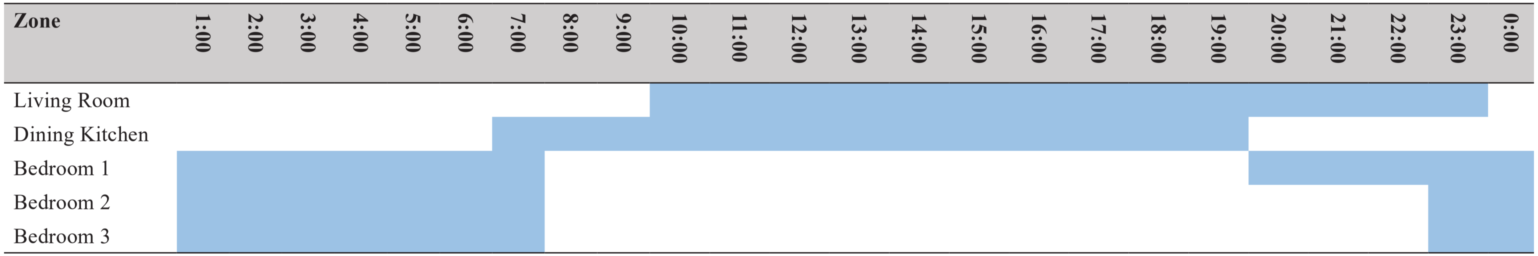
Table 5
Internal heat generation schedule of Type C (weekdays)

Heat gain	**1:00**	**2:00**	**3:00**	**4:00**	**5:00**	**6:00**	**7:00**	**8:00**	**9:00**	**10:00**	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**17:00**	**18:00**	**19:00**	**20:00**	**21:00**	**22:00**	**23:00**	**0:00**
Human body [W]	0	0	0	0	0	0	0	0	0	100	100	100	0	0	100	100	0	0	0	100	100	200	200	0
Lighting [W]	4	4	4	4	4	4	40	40	40	40	4	4	4	4	4	4	4	40	40	40	40	40	40	4
TV [W]	16	16	16	16	16	16	162	162	162	162	162	162	162	16	16	16	16	162	162	162	162	162	162	16
Human body [W]	0	0	0	0	0	0	100	400	0	0	0	0	100	0	0	0	0	100	200	0	200	0	0	0
Lighting [W]	4	4	4	4	4	4	40	40	40	40	4	4	4	4	4	4	4	40	40	40	40	40	40	4
IH [W]	12	12	12	12	12	12	400	12	12	12	12	12	12	12	12	12	12	400	12	12	12	12	12	12
Refrigerator [W]	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11
Rice cooker [W]	15	15	15	15	15	150	15	15	15	15	15	15	15	15	15	15	15	150	15	15	15	15	15	15
Human body [W]	200	200	200	200	200	200	100	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	0	200
Lighting [W]	4	4	4	4	4	4	40	4	4	4	4	4	4	4	4	4	4	4	4	4	40	40	4	40
Personal computer [W]	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	30	30	3	3
Human body [W]	100	100	100	100	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100
Lighting [W]	4	4	4	4	4	4	40	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	40	40
Human body [W]	100	100	100	100	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100
Lighting [W]	4	4	4	4	4	4	40	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	40	40
Washing machine [W]	14	14	14	14	14	14	14	14	82	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14
Hair dryer [W]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	100	0	0
Vacuum cleaner [W]	0	0	0	0	0	0	0	0	83	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 6
Internal heat generation schedule of Type C (weekend)

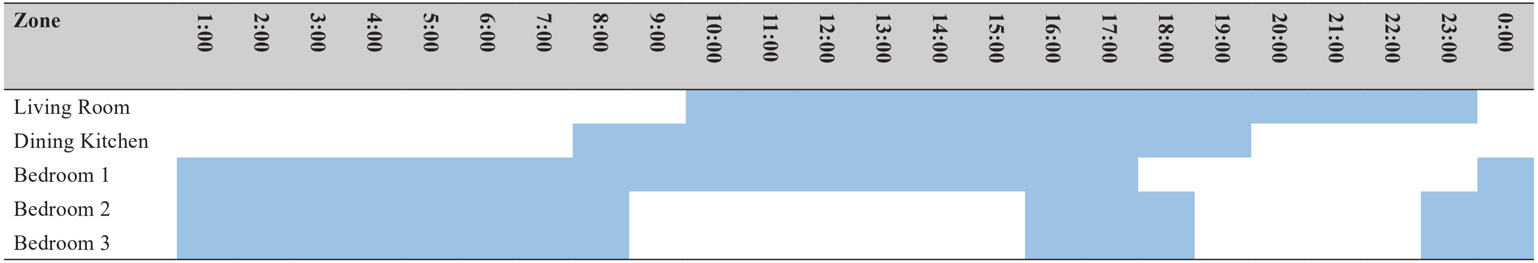
Zone	Heat gain	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	0:00
Living Room	Human body [W]	0	0	0	0	0	0	0	0	0	100	100	100	100	0	0	100	100	100	0	300	300	200	200	0
	Lighting [W]	4	4	4	4	4	4	4	40	40	40	4	4	4	4	4	4	40	40	40	40	40	40	40	4
	TV [W]	16	16	16	16	16	16	16	162	162	162	162	162	162	162	162	162	162	162	162	162	162	162	162	16
Dining Kitchen	Human body [W]	0	0	0	0	0	0	0	100	400	0	0	0	100	200	0	0	0	100	400	0	0	0	0	0
	Lighting [W]	4	4	4	4	4	4	4	40	40	40	4	4	4	4	4	4	40	40	40	40	40	40	40	4
	IH [W]	12	12	12	12	12	12	12	400	12	12	12	12	12	12	12	12	12	400	12	12	12	12	12	12
	Refrigerator [W]	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11
	Rice cooker [W]	15	15	15	15	15	15	150	15	15	15	15	15	15	15	15	15	15	150	15	15	15	15	15	15
Bedroom 1	Human body [W]	200	200	200	200	200	200	200	100	0	100	100	100	0	0	100	100	100	0	0	0	0	0	0	200
	Lighting [W]	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	40	4	4	4	4	4	4	40
	Personal computer [W]	3	3	3	3	3	3	3	3	3	30	30	30	3	3	3	3	3	3	3	3	3	3	3	3
Bedroom 2	Human body [W]	100	100	100	100	100	100	100	100	0	0	0	0	0	0	0	0	100	100	0	0	0	100	100	100
	Lighting [W]	40	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	40	40	4	4	4	40	40	40
Bedroom 3	Human body [W]	100	100	100	100	100	100	100	100	0	0	0	0	0	0	0	0	100	100	0	0	0	100	100	100
	Lighting [W]	40	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	40	40	4	4	4	40	40	40
Others	Washing machine [W]	14	14	14	14	14	14	14	14	14	14	82	14	14	14	14	14	14	14	14	14	14	14	14	14
	Hair dryer [W]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	0	0	0
	Vacuum cleaner [W]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	83	0	0	0	0	0	0	0	0	0

Table 7
Heating and cooling schedule of Type A (weekdays)



Zone	**1:00**	**2:00**	**3:00**	**4:00**	**5:00**	**6:00**	**7:00**	**8:00**	**9:00**	**10:00**	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**17:00**	**18:00**	**19:00**	**20:00**	**21:00**	**22:00**	**23:00**	**0:00**
Living Room										🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	
Dining Kitchen							🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦					
Bedroom 1	🟦	🟦	🟦	🟦	🟦	🟦	🟦													🟦	🟦	🟦	🟦	🟦
Bedroom 2	🟦	🟦	🟦	🟦	🟦	🟦	🟦																🟦	🟦
Bedroom 3	🟦	🟦	🟦	🟦	🟦	🟦	🟦																🟦	🟦

Table 8
Heating and cooling schedule of Type A (weekend)



Zone	**1:00**	**2:00**	**3:00**	**4:00**	**5:00**	**6:00**	**7:00**	**8:00**	**9:00**	**10:00**	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**17:00**	**18:00**	**19:00**	**20:00**	**21:00**	**22:00**	**23:00**	**0:00**
Living Room										🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	
Dining Kitchen								🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦					
Bedroom 1	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦							🟦
Bedroom 2	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦								🟦	🟦	🟦					🟦	🟦
Bedroom 3	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦								🟦	🟦	🟦					🟦	🟦

Table 9
Heating and cooling schedule of Type B (weekdays)

Zone	**1:00**	**2:00**	**3:00**	**4:00**	**5:00**	**6:00**	**7:00**	**8:00**	**9:00**	**10:00**	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**17:00**	**18:00**	**19:00**	**20:00**	**21:00**	**22:00**	**23:00**	**0:00**
Living Room										■	■	■	■	■	■	■	■	■	■	■	■	■	■	
Dining Kitchen							■	■	■	■	■	■	■	■	■	■	■	■	■					
Bedroom 1	■	■	■	■	■	■	■																	■
Bedroom 2	■	■	■	■	■	■	■															■	■	■
Bedroom 3	■	■	■	■	■	■	■															■	■	■

Table 10
Heating and cooling schedule of Type B (weekend)

Zone	**1:00**	**2:00**	**3:00**	**4:00**	**5:00**	**6:00**	**7:00**	**8:00**	**9:00**	**10:00**	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**17:00**	**18:00**	**19:00**	**20:00**	**21:00**	**22:00**	**23:00**	**0:00**
Living Room										■	■	■	■	■	■	■	■	■	■	■	■	■	■	
Dining Kitchen							■	■	■	■	■													
Bedroom 1	■	■	■	■	■	■	■	■	■	■	■													■
Bedroom 2	■	■	■	■	■	■	■								■	■	■	■						■
Bedroom 3	■	■	■	■	■	■	■								■	■	■	■						■

Table 11
Heating and cooling schedule of Type C (weekdays)

Zone	**1:00**	**2:00**	**3:00**	**4:00**	**5:00**	**6:00**	**7:00**	**8:00**	**9:00**	**10:00**	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**17:00**	**18:00**	**19:00**	**20:00**	**21:00**	**22:00**	**23:00**	**0:00**
Living Room										■	■	■	■	■	■	■	■	■	■	■	■	■	■	
Dining Kitchen							■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			
Bedroom 1	■	■	■	■	■	■	■														■	■	■	■
Bedroom 2	■	■	■	■	■	■	■																■	■
Bedroom 3	■	■	■	■	■	■	■																■	■

Table 12
Heating and cooling schedule of Type C (weekend)

Zone	**1:00**	**2:00**	**3:00**	**4:00**	**5:00**	**6:00**	**7:00**	**8:00**	**9:00**	**10:00**	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**17:00**	**18:00**	**19:00**	**20:00**	**21:00**	**22:00**	**23:00**	**0:00**
Living Room										■	■	■	■	■	■	■	■	■	■	■	■	■	■	
Dining Kitchen								■	■	■	■	■	■	■	■	■	■	■	■					
Bedroom 1	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■							■
Bedroom 2	■	■	■	■	■	■	■	■									■	■				■	■	■
Bedroom 3	■	■	■	■	■	■	■	■									■	■				■	■	■

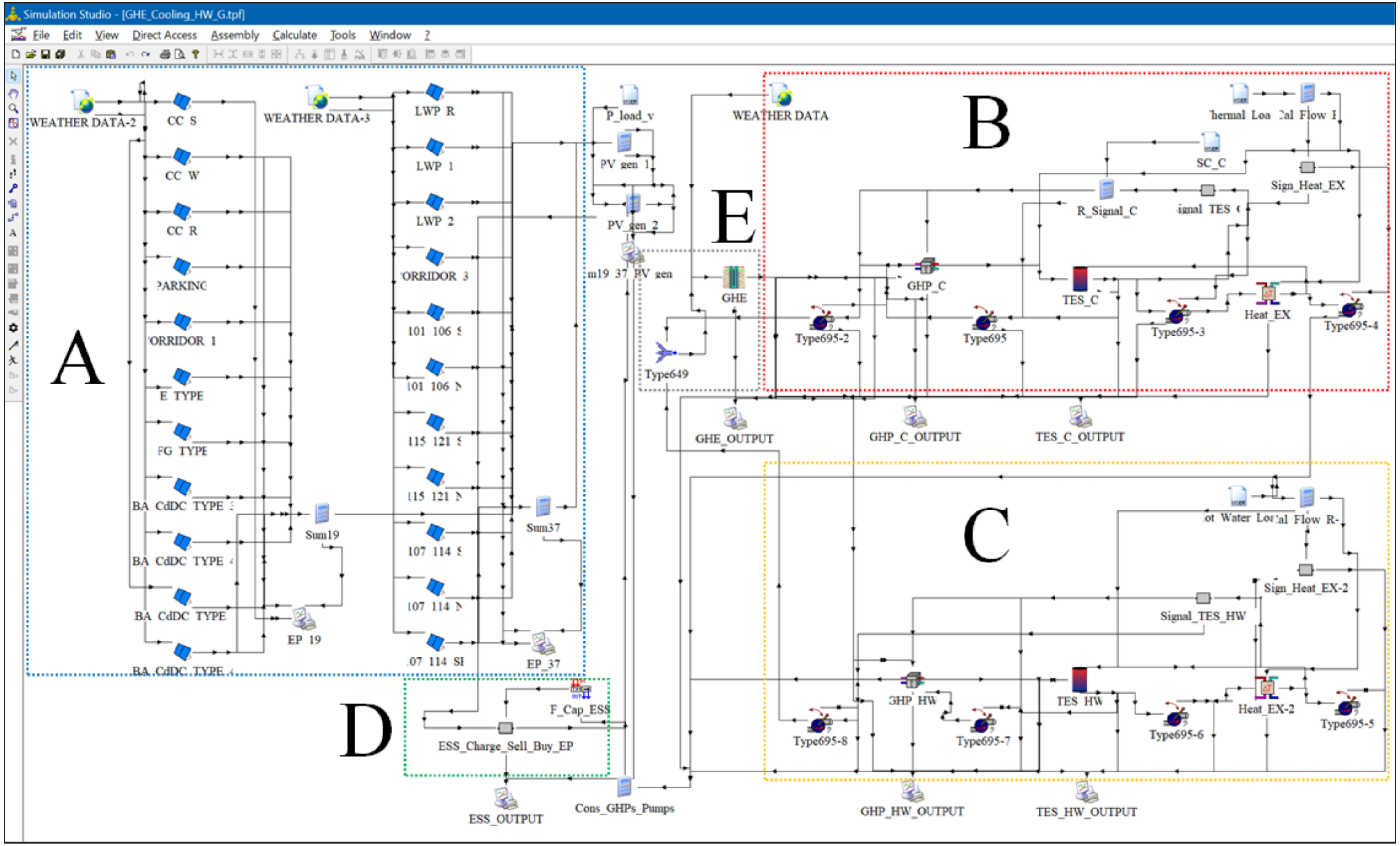


Figure 5. Setting screen of the file that was analyzed by TRNSYS

Table 13
Heat transfer coefficient of each construction type

Construction type	**External wall**	**Internal wall**	**Floor**	**Interlayer slabs**
U-value (W/(m2·K))	0.147	2.044	0.138	0.806
Construction type	Roof	Metal door	Wood door	Window (triple glass)
U-value (W/(m2·K))	0.103	0.151	0.935	0.580

Electricity Sharing System

As shown in Figure 4, photovoltaic panels were installed not only on the roofs of the houses but also in parking lots, community centers, and passages in the target housing complexes. Tables 14 and 15 show the specifications of photovoltaic panels installed in the housing complexes and the rated capacity, azimuth, and tilt angles of photovoltaic panels by installation location. Additionally, the interconversion rate between DC and AC electricity when charging the generated electricity and discharging the storage battery was set to 0.98.

Table 14
Specifications of photovoltaic panels

Reference cell temperature [℃]	**25**
Reference solar radiation [W/㎡]	1000
Temperature coefficient of short circuit current [A/K]	0.00043
Temperature coefficient of release voltage [V/K]	-0.00277
Number of cells connected in series within a module [pieces]	78
Nominal operating cell temperature [℃]	45

Table 15
Related capacity of photovoltaic module, azimuth, and tilt angles of photovoltaic panels

Installation location	**Rated capacity of photovoltaic module [W]**	**Azimuth [°]**	**Tilt angle [°]**
Parking lot	450	-28.00	15.00
Community Center	360	-28.00	90.00
House	430	-35.00	22.52
Passage 1	450	-2.50	48.30
Passage 2	430	-2.50	48.30

Table 16 shows the specifications of storage batteries. Power Conditioning System (PCS) capacity is the performance that can charge and discharge electricity from a storage battery per hour.

Table 16
Specifications of storage batteries

Electricity storage capacity [kWh]	**400**
Minimum charging rate	0.2
Maximum charging rate	0.8
PCS capacity[kW]	200
Charge/discharge rate	0.98

Considering electricity consumption, photovoltaic power generation, remaining capacity of storage batteries, electricity storage rate, and discharge rate, it had to be determined whether to sell, purchase, or store electricity. Thus, a new component was added to TRNSYS to perform this determination on the calculation. The added component is D in Figure 4. Figure 6 shows the logic of determining the judgment in the newly added component.

Economic Evaluation

Depending on the presence or absence of photovoltaic power generation and the target for the sale of surplus electricity, costs and profits are calculated for the following three conditions. First, all the electricity required in housing complexes is purchased from the electricity company. Photovoltaic power generation is not considered in this condition. When the photovoltaic power generation is greater than the electricity consumption, profits are calculated for two conditions: selling surplus electricity to nearby houses or electricity companies. In the opposite case, the cost of purchasing insufficient electricity from an electricity company is calculated. The price for selling photovoltaic power to an electricity company was 171 KRW/kWh, and that for selling to nearby houses was 187 KRW/kW. In addition, the price of purchasing electricity from an electricity company was 234.3 KRW/kWh (https://cyber.kepco.co.kr/ckepco/front/jsp/CY/J/A/CYJAPP000NFL.jsp). When calculating the electricity transmission loss, the resistance on one line of the high voltage was 0.103 Ω/km; the transmission voltage was 6600 V, and the transmission distance was assumed to be 0.13 km when transmitting from the housing complexes to nearby houses and 10 km when transmitting to the electricity company. The electricity loss in the pole transformer was assumed to be 3%.

Environmental Evaluation

CO_2 emissions when using thermal power-generated electricity for all the electricity consumed in the housing complexes and when using thermal power-generated electricity only for electricity insufficient for photovoltaic power generation, that is, the amount of electricity purchased, were compared. As much as the electricity obtained by photovoltaic

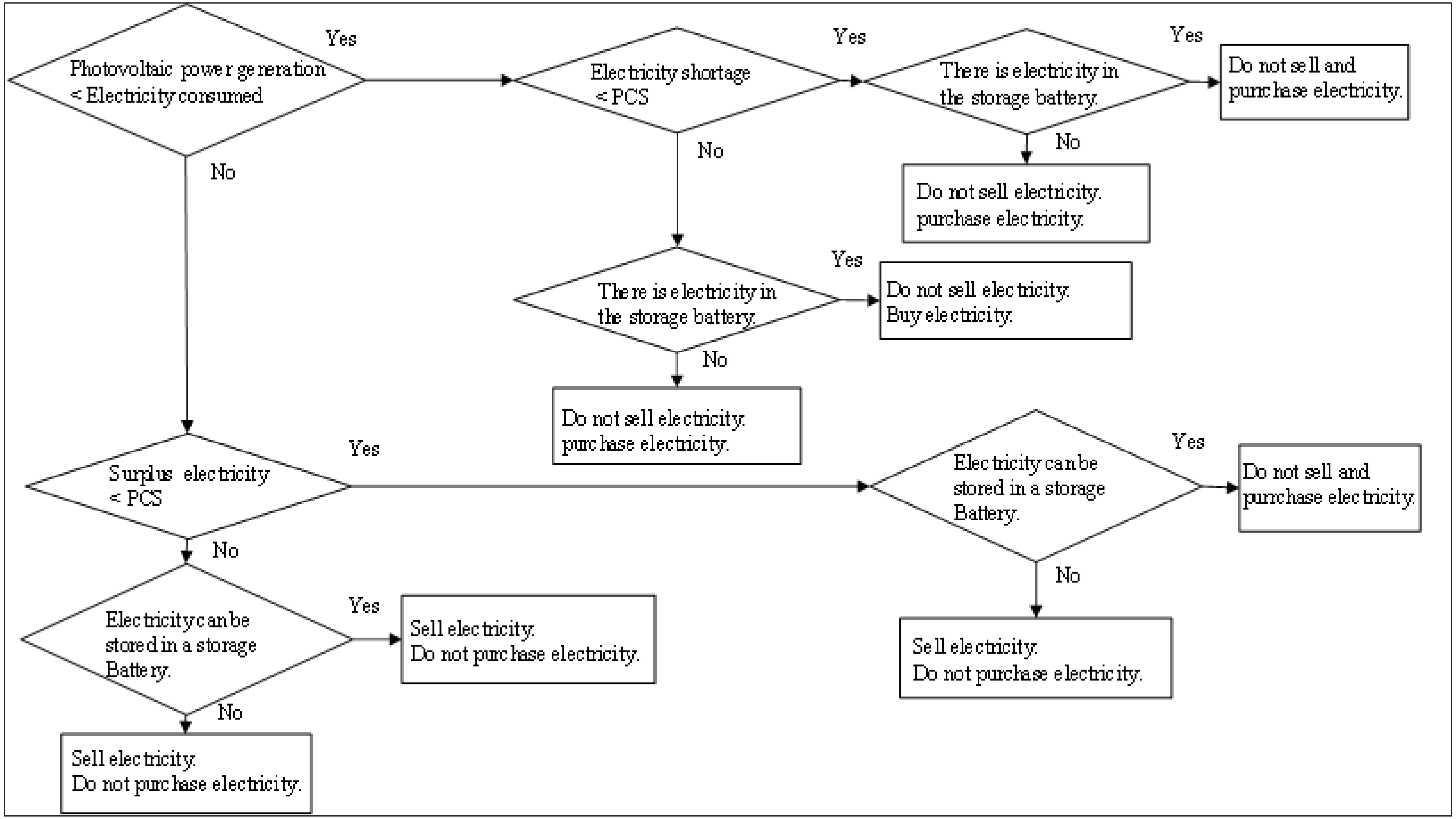


Figure 6. Flowchart for the determination of electricity sharing, selling, or buying

power generation, fossil fuels for thermal power generation are reduced, and CO_2 emissions generated during the combustion of fossil fuels are also reduced. Therefore, the reduction ratio of CO_2 emissions according to each type of fossil fuel matches the ratio of purchased electricity according to the presence or absence of solar power generation. Three types of fuel are mainly used in the case of thermal power generation: liquefied natural gas (LNG), coal, and oil. Thus, CO_2 emission was compared for power generation using these three types of fossil fuels. The unit calorific value of coal was 25.7 MJ/kg, the unit calorific value of LNG was 54.6 MJ/kg, and the unit calorific value of heavy oil A was 39.1 MJ/kg. The unit CO2 emissions of coal, heavy oil A and LNG were set at 2.419 kgCO2/kg, 3.151 kgCO2/kg and 2.698 kgCO2/kg, respectively. In addition, the energy conversion efficiency of thermal power generation was assumed to be 43%.

RESULTS AND DISCUSSION

Electricity Generation, Surplus Electricity Sale

Figure 7 shows the monthly electricity generation by photovoltaic panels. Figure 8 shows the monthly surplus electricity obtained by subtracting electricity consumption from photovoltaic generation. According to the calculation results, the annual photovoltaic power generation in the housing complexes was 556 MWh—3.1 times the annual electricity consumption of 180 MWh. In addition, as shown in Figure 8, electricity generation exceeded power consumption in all months; thus, the electricity generation performance of the target housing complexes was sufficient. The annual electricity purchase of the target housing complexes was 87 MWh—a 52% reduction in annual electricity purchases by introducing an electricity sharing system compared to when electricity companies purchased all electricity consumed annually without photovoltaic power generation. In

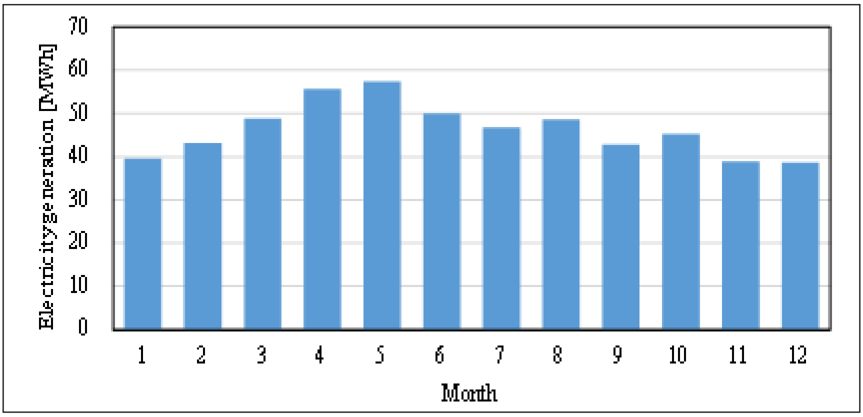


Figure 7. Monthly electricity generation by photovoltaic panels. the annual photovoltaic power generation in housing complexes was 556 MWh

addition, the annual electricity sale was 433 MWh, meaning that 77.8% of the electricity generated annually was sold; 14.1% (25.4 MWh) of the annual electricity consumption of 180 MWh was discharged from the storage battery.

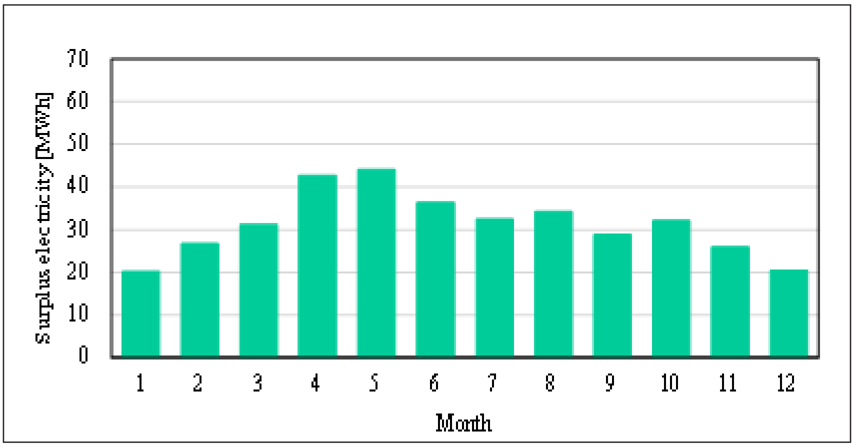


Figure 8. Monthly surplus electricity obtained by subtracting electricity consumption from photovoltaic generation. Electricity generation exceeded power consumption in all months

Economic Evaluation

Figure 9 shows the annual electricity charges per household for 56 households in the housing complexes, divided into cases in which all electricity consumption was purchased, surplus electricity was sold to nearby houses, and surplus electricity was sold to electricity

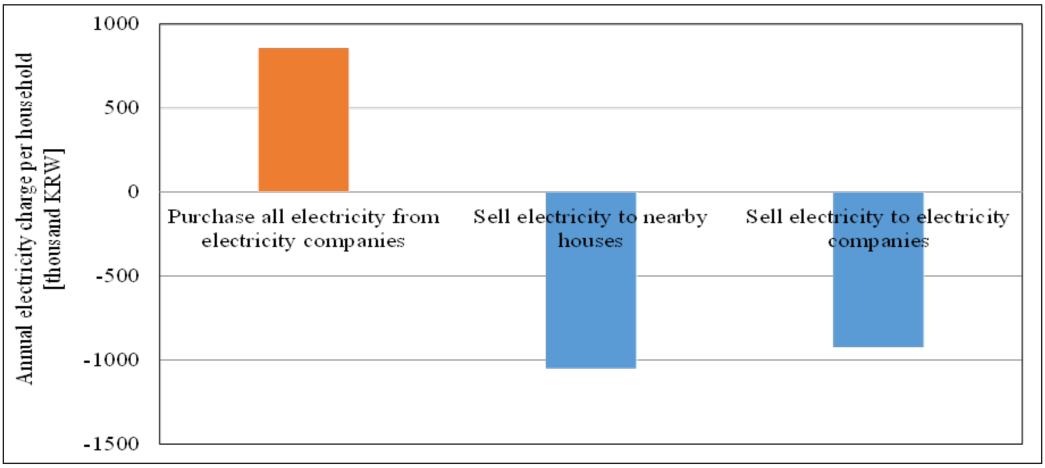


Figure 9. Annual electricity charges per household for 56 households in a housing complex. Selling surplus electricity directly to nearby houses can be expected to yield about 1.14 times the profit compared to selling to electricity companies

companies. Electricity charges per household were not applied to progressive rates according to electricity consumption. If all the power consumed was purchased from an electricity company, the annual electricity charge per household was 856.8 thousand KRW. In contrast, if surplus electricity was sold to a nearby house or power company, the profit was 1049.2 thousand KRW or 921.0 thousand KRW, respectively. Therefore, selling surplus electricity directly to nearby houses can yield about 1.14 times the profit compared to selling to electricity companies.

Figure 10 shows the electricity transmitted when surplus electricity was sold to nearby houses and sold to an electricity company. This difference is because transmission loss is considered according to transmission distance. Based on the electricity transmitted from the target housing complexes, the proportion of the electricity received by nearby houses was 94.08%; for electricity companies, it was 93.27%. However, the efficiency of electricity reception when transmitting electricity to a nearby house is only about 0.81% different from that when transmitting electricity to an electricity company and retransmitting it to consumers. Accordingly, the effect of transmission distance on transmission loss is significantly small.

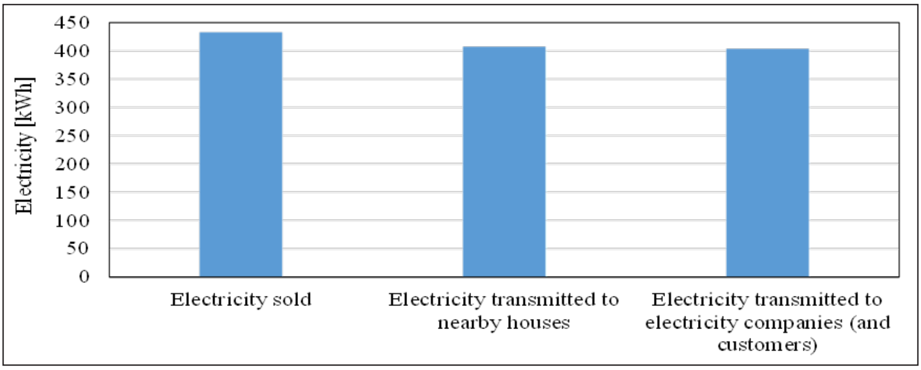


Figure 10. Actual electricity was transmitted when surplus electricity was sold to nearby houses and sold to an electricity company. The effect of transmission distance on transmission loss is significantly small

Environmental Evaluation

Figure 11 shows the requirements of coal, LNG, and heavy oil A when using only electricity generated by thermal power and electricity generated by photovoltaic power first, then making up for the shortfall by thermal power generation. Figure 12 shows CO_2 emissions when generated using these fossil fuels. Using electricity generated by photovoltaic power first and making up for the shortage with thermal power generation can reduce the amount of fossil fuel and CO_2 emissions by 56.2% compared to using only electricity generated by thermal power, regardless of the type of fossil fuel of coal, LNG, and heavy oil A.

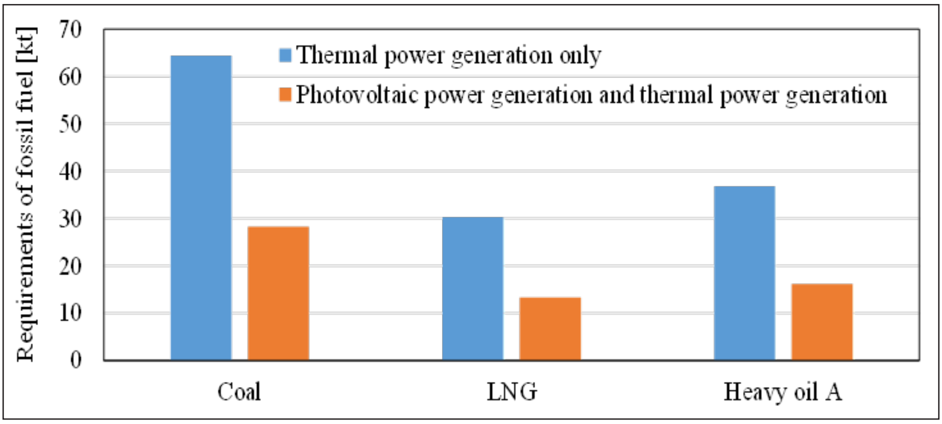


Figure 11. Requirements of coal, LNG, and heavy oil A needed for electricity generation

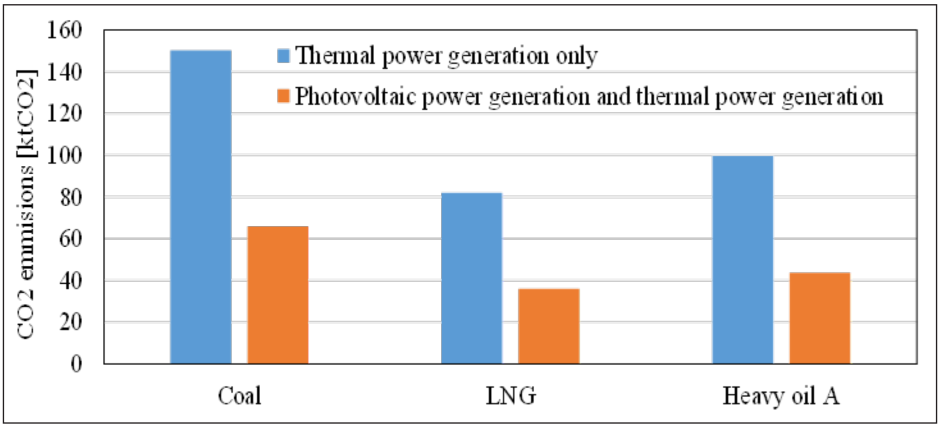


Figure 12. CO_2 emissions when generated using coal, LNG, and heavy oil A. The proposed energy-sharing system can reduce CO_2 emissions by about 56.2%

CONCLUSION

In this study, photovoltaic panels and large-capacity storage batteries were installed as distributed energy systems in the housing complexes. TRNSYS simulation evaluated whether the proposed electricity sharing system could enable a stable use of electricity by offsetting its surplus and shortage due to differences in family composition and lifestyle patterns. In addition, this study economic and environmental evaluations of the proposed electricity sharing system and drew the following conclusion:

1. A method of storing electricity generated during the day in the storage battery is useful as a time gap exists between the daytime when photovoltaic power generation is available and the morning and evening hours when electricity consumption is concentrated.

2. Photovoltaic panels were installed in parking lots, corridors, community centers, and roofs of entire housing complexes—not single houses—to offset the surplus and shortage of electricity due to differences in family composition and lifestyle patterns. The electricity generated was stored in a large-capacity storage battery.
3. Housing complexes primarily consume electricity generated by photovoltaic panels. Then, to make profits, surplus electricity was supplied to nearby houses at a lower price than the electricity company's supply price and at a higher price than when selling electricity to the electricity company.
4. TRNSYS was added with a new component to determine whether to sell, purchase or store electricity. This component considers electricity consumption, photovoltaic power generation, the remaining capacity of storage batteries, the electricity storage rate, and the discharge rate.
5. The annual photovoltaic power generation in the target housing complexes was 3.1 times the annual electricity consumption, and monthly photovoltaic power generation also exceeded the electricity consumption in all months.
6. As an economic benefit, 1049.2 KRW was generated annually when surplus electricity from photovoltaic power generation was sold to nearby houses.
7. Using electricity generated by photovoltaic power first and making up for the shortage with thermal power generation can reduce fossil fuel and CO_2 emissions by 56.2%.

The above analysis confirmed that the proposed electricity-sharing system could supply stable electricity and have excellent economic and environmental performance. As a future task, it will be necessary to examine not only a method of storing surplus electricity in a storage battery but also one of predicting future thermal load, as well as storing cold or warm heat in a thermal energy storage tank in advance using surplus electricity.

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