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Comparative Analysis of Estimated and Actual Power Self-Sufficiency Rates in Energy-Sharing Communities with Solar Power Systems

Dawon Kim [1,†], Yonghae Jang [2,†] and Yosoon Choi [1,*]

[1] Department of Energy Resources Engineering, Pukyong National University, Busan 48513, Republic of Korea; da1202256057@pukyong.ac.kr
[2] Busan Eco Delta City Project Group, Korea Water Resource Corporation, Busan 46717, Republic of Korea; kaka1220@kwater.or.kr
* Correspondence: energy@pknu.ac.kr; Tel.: +82-51-629-6562; Fax: +82-51-629-6553
† These authors contributed equally to this work.

Abstract: Amid the ongoing climate crisis, the international community is enacting policies to promote low-carbon energy-sharing communities. The primary objective of such communities is to enhance community-level energy self-sufficiency. Accurate energy self-sufficiency assessments are paramount in planning energy-efficient architectural designs, urban landscapes, and communal environments. In this study, the energy self-sufficiency rate of an energy-sharing community was estimated at the design stage and compared with the actual energy self-sufficiency rate calculated based on data collected over the following year (April 2022 to March 2023). The outcomes reveal that the estimated energy self-sufficiency rate is 171%, whereas the realized rate is 133%, underscoring the disparity between the projections and outcomes. An analysis of the seasonal variations in these discrepancies elucidated a correlation between the differences in the insolation levels between standard typical meteorological year (TMY) data that are conventionally used for energy generation projections and the actual meteorological conditions. Moreover, a notable incongruity surface exists between the monthly average electricity consumption of a standard four-person household, as stipulated by the Korean Electric Power Corporation (KEPCO) at 273 kWh, and the empirical power consumption at 430 kWh, resulting in a variance of approximately 157 kWh. This study illuminates the complex relationship between variables affecting energy self-sufficiency in energy-sharing communities. It serves as a crucial step towards informed decision making and precision in sustainable urban energy solutions.

Keywords: renewable energy; photovoltaic system; energy self-sufficient rate; energy-sharing community; energy analysis

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1. Introduction

Recently, cities and local communities worldwide have faced unprecedented challenges due to natural disasters' escalating frequency and severity, primarily induced by the ongoing climate change crisis. In light of this heightened awareness of the climate crisis, efforts to concretize international energy transitions have been made, concurrently accentuating the imperative for energy transformation. According to a UN survey, approximately 60% of the world's population is projected to reside in 100 major cities [1]. These urban centers are expected to consume 78% of the world's energy and account for over 60% of global greenhouse gas emissions [2]. Densely populated cities play a pivotal role in reducing carbon emissions because they are the best locations for deploying clean, energy-efficient, and sustainable technologies [3,4]. Governments worldwide, in collaboration with international organizations, are actively pursuing policies to regulate future energy-related discussions and promote the proliferation of energy-sharing communities centered around cities as part of their efforts to achieve net-zero emissions by 2050.

Among its major cities, the United States is building green cities. New York City enacted the Climate Mobilization Act in April 2019 with the aim of reducing greenhouse gas emissions from large buildings by up to 70% by 2050 [5]. Similarly, Los Angeles has developed a Sustainable City Plan that includes initiatives such as feasibility studies for solar power generation systems in multifamily households and programs for installing solar power systems in low-income communities [6]. The EU has undertaken initiatives such as the City-Zen project to promote the construction of clean-energy cities. This project aims to improve energy efficiency by renovating buildings and integrating energy systems [7]. China is committed to implementing green building standards in newly constructed urban buildings by 2025. Furthermore, China is progressively reducing energy consumption through energy-saving renovations of residential and public buildings while enhancing research and development initiatives for low-carbon technologies [8]. The Japanese government is actively pursuing policies to expand the adoption of solar power, including policies to increase solar panel installations in buildings and apartments from 2040 onwards. In addition, they established a Power Purchase Agreement (PPA) framework to facilitate the expansion of solar power generation and ensure grid capacity for integration [9]. Since 2021, the Malaysian government has promoted the installation of rooftop solar power generation facilities through the NEM3.0 initiative. Additionally, they implemented energy efficiency standards for household appliances in accordance with the National Energy Efficiency Action Plan from 2016 to 2025 [10,11]. Korea is advancing its eco-energy town project by expanding the concept of energy-neutral units and focusing on zero-energy buildings. To enhance energy efficiency, they defined incremental levels of zero-energy building concepts, with plans to expand the adoption of zero-energy buildings in private construction projects starting in 2025 [12]. Although there may be variations in approaches between countries, proactive policies have led to the emergence of energy-sharing communities worldwide.

Viikki Village, created through a combination of the Finnish government, residents, and the environment, operates as an ecologically sustainable zero-energy town by actively supporting R&D, utilizing new and renewable energy, and monitoring energy data [13]. The BedZED complex in the UK is an eco-friendly complex that has achieved self-sufficiency rates of 85% for heating and 45% for electricity using energy-saving architectural designs, solar power generation, and biomass plants. This energy self-sufficient community is designed to sustain life solely with the energy it produces within its boundaries [14]. Germany, known for its active involvement in eco-friendly urban development projects, has the Vauban District in Freiburg. All houses in the Vauban community are passive houses that were designed to minimize internal energy loss through insulation. With its low energy efficiency, the Vauban district can save over 70% more energy than typical German houses [15]. Additionally, there are energy-sharing communities in Vauban that utilize various technologies, including renewable energy and energy storage systems (ESSs) [16–19].

The purpose of a low-carbon energy-sharing community is to increase the energy self-sufficiency rate of the community by increasing the energy produced rather than the energy consumed. Various energy technology certification criteria have been used to evaluate energy efficiency. Switzerland has adopted Minergie as a standard for buildings. The Minergie criteria, calculated based on building type, consider the total energy demand. Certification is granted when a building satisfies the minimum energy demand requirements, electricity self-sufficiency, and other comprehensive assessments [20]. The United Arab Emirates introduced the Emirates Energy Star (EES) rating system in 2010 to evaluate the energy efficiency of buildings and assign ratings based on energy-saving ratios [21]. Vietnam employs two certification systems for green buildings: the Leadership in Energy and Environmental Design (LEED) rating system and a tool developed by the Vietnam Green Building Council (VGBC) known as LOTUS. These systems are certified on the basis of specific criteria related to environmental sustainability and energy efficiency [22]. In

South Korea, three evaluation standards exist: building energy efficiency grades, energy self-sufficiency rates, and evaluation methods that use Building Energy Management Systems (BEMSs) or remote metering electronic meters. Many studies have used the energy self-sufficiency rate as an evaluation indicator to assess energy efficiency [23–33]. The energy self-sufficiency rate refers to the ability to meet the energy demand using a certain degree of local energy sources [34]. In zero-energy smart cities aimed at maximizing energy efficiency, it is crucial to consider city-level self-sufficiency rates during the planning phase. This consideration is related to the analysis of land use plans and the economic feasibility of projects. Therefore, an accurate estimation of the energy self-sufficiency rate is required during the building, city, and community design phases [28].

Therefore, it is time to research methods to calculate the self-reliance rate of energy-sharing communities to increase the proportion of renewable energy sources. In addition, to increase energy self-sufficiency, accurate predictions for actual buildings, rather than predictions based on past data, are becoming necessary for planning and economic feasibility analyses in the development planning stage of smart cities and energy-sharing communities. Hence, there is a need for research related to the difference between the self-sufficiency rate estimated at the developmental planning stage and the actual self-reliance rate and cause analysis. Previous studies have estimated or calculated self-sufficiency rates. However, there is a lack of prior research that compares the estimated self-sufficiency rates during the building or city design phase with the actual post-design self-sufficiency rates and conducts a detailed analysis of the underlying causes.

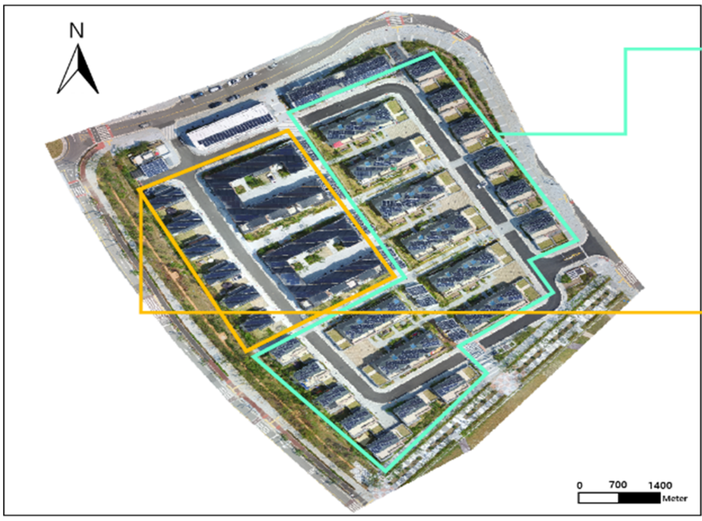
We assume that the estimated energy self-sufficiency rate in the design stage will be more than 20% different from the calculated energy self-sufficiency rate in the operation stage, and we want to check the error and identify the cause by comparing the estimated energy self-sufficiency rate and the calculated value. A smart city selected as a national pilot smart city was selected as a research area, and it will be a case that can be used in the future when designing such a city. Data on design parameters and environmental conditions were obtained for 56 houses to estimate and calculate power generation and consumption for one year in the study area. Then, the energy self-sufficiency rate was calculated by collecting PV power generation and electricity consumption data of the study area that are the actual data. The estimated energy independence rate and the actual value were separated into total, district, and season based on each household, and the differences were compared.

This paper is organized as follows. Section 2 describes the study area. Section 3 suggests the research methodology for estimating and calculating the energy self-sufficiency rate. Section 4 presents the results of the comparison between the estimated energy self-sufficiency rate and the actual energy self-sufficiency value for the study area, followed by the discussion and conclusion in Sections 5 and 6.

2. Study Area and Data

This study selected a smart complex located in Gangseo-gu, Busan, South Korea as the target for analyzing the energy-sharing community sufficiency rate. The study area is located in the wide delta plain at the mouth of the Nakdong River. It is a gently sloping area with a slope of less than 5°, and it is flat at an altitude of approximately 10 m. The average annual temperature is 14.8°, and the annual precipitation is 1397 mm, which is 2° higher than the average annual temperature of South Korea (12.8°) and similar to the average annual precipitation (1358 mm). The village, which consists of 56 households in 29 buildings, has a land area of 7202 m^2, a built-up area of 2200 m^2, and a gross floor area of 3620 m^2. Of the 56 households, 18 are detached houses with two to three floors, and the remaining 38 are attached houses with two to three households per building. All of the buildings do not use gas-fired heating systems, and they use electricity for cooling and heating energy, so they are installed with photovoltaic systems on the roofs. The 29 buildings vary in size, type (detached/attached house), installed PV systems, and inverters, so this study classifies them into two complexes and eight building types based on these differences.

First, we classified the buildings into two complexes based on the number of PV modules and inverters installed (Figure 1). PV modules with a power of 85 Wp and an efficiency of about 0.6% higher than the first were used in the second complex, and two inverters were installed in each household. Only one building (type f) had only one inverter installed.



- The first complex

Photovoltaic panel	Value
Peak power(Pmax)	360Wp
Efficiency	19.90%
Maximum power voltage(Vmp)	39.5V
Maximum power current(Imp)	9.13A
Open circuit volage(Voc)	47.7V

- The second complex

Photovoltaic panel	Value
Peak power(Pmax)	445Wp
Efficiency	20.50%
Maximum power voltage(Vmp)	41.25V
Maximum power current(Imp)	10.80A
Open circuit volage(Voc)	49.45V

Figure 1. View of the energy-sharing community.

The 29 buildings were divided into eight types, A, B, C, D, E, F, f, and G, according to the number, arrangement of PVs installed, and households in each building, as shown in Figure 2. The information for each type is summarized in Table 1. A, D, E, and F are detached houses, and B, C, f, and G are attached houses. Among the attached houses, B and C have three households, f has two households, and G has six households living in one building. The number of solar panels installed in the attached houses is higher than in the detached houses, but the number of panels per household is similar: 13.75 for detached houses and 13.29 for attached houses. However, f has the smallest capacity with nine panels, and the number of households is two, so the number of panels that can be used by a household is small, at about 4.5.

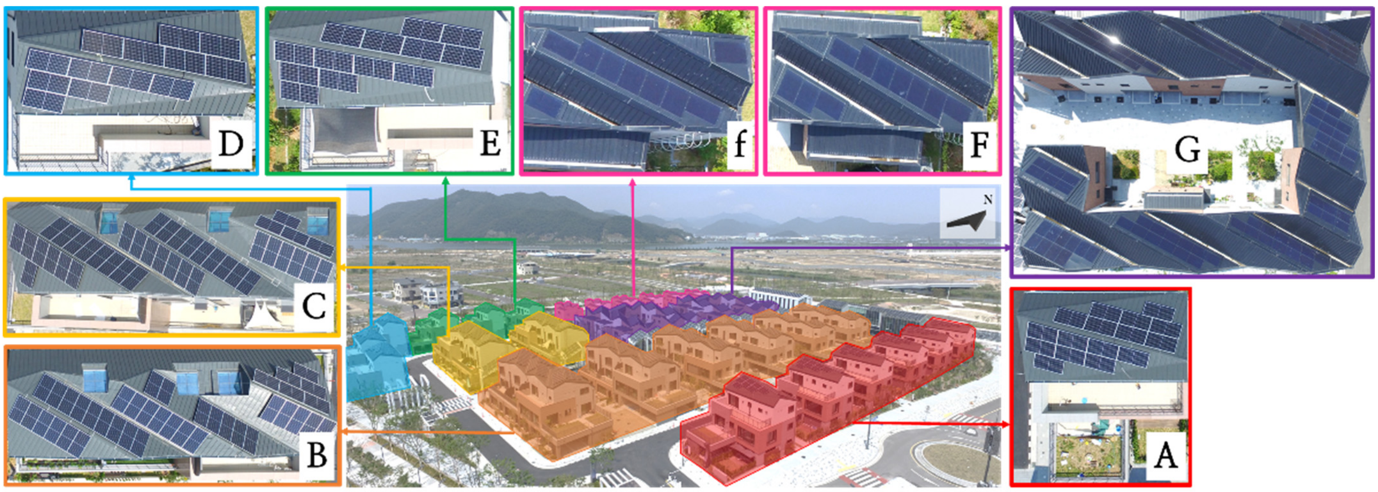


Figure 2. 29 Buildings divided into 8 sessions and PV systems installed differently in each building.

Table 1. Information for each of the 8 sections.

Section ID	A	B	C	D	E	F	f	G
Number of buildings	6	6	2	4	3	5	1	2
Number of households	6	18	6	4	3	5	2	12
Number of PVs	16	40	41	13	13	10	9	96
Number of inverters	12	36	12	8	6	10	4	24
Area of the house (pyeong)	47	26	26	39	39	30	30	29
House type	Detached	Attached	Attached	Detached	Detached	Detached	Attached	Attached

3. Methods

In this study, we estimated the energy self-sufficiency rate of the study area during the design process and compared it with the actual energy self-sufficiency rate. The energy self-sufficiency rate comparison process is divided into three stages, as shown in Figure 3.

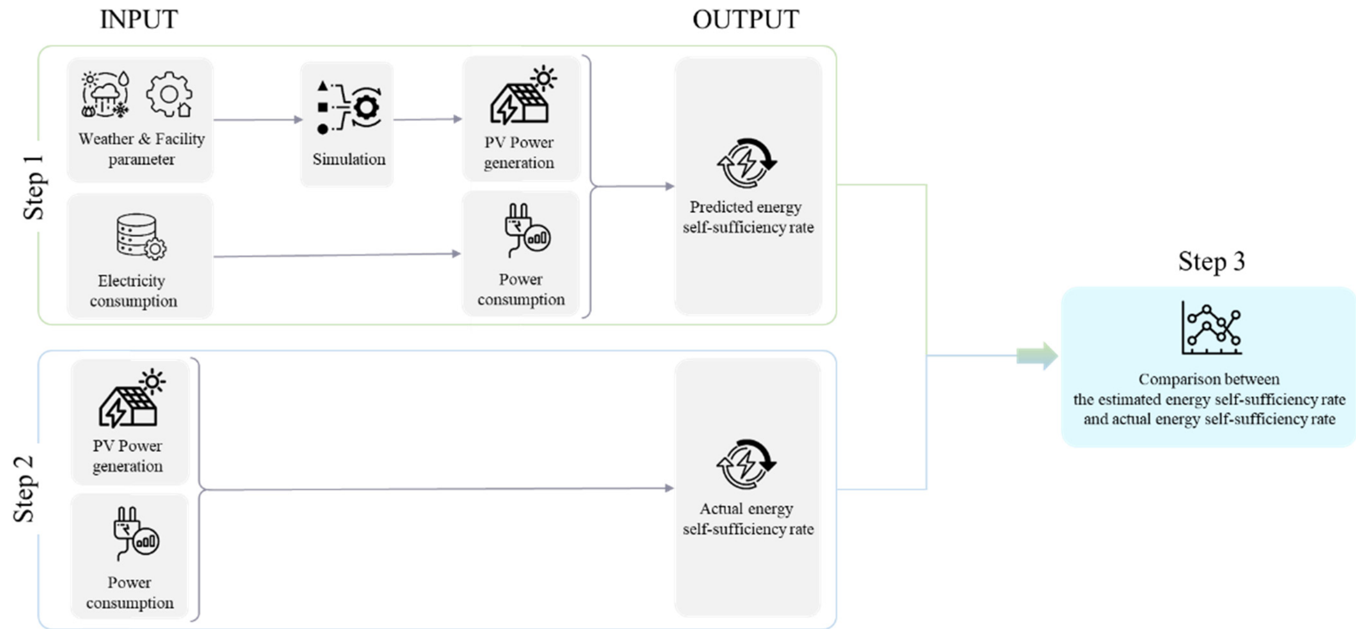


Figure 3. Step-by-step process for energy self-sufficiency rate comparison.

First, solar power generation facilities in the study area were selected based on the design plan and weather information to estimate the energy self-sufficiency rate at the design stage. Based on the collected data, the NREL's (National Renewable Energy Laboratory, Golden, CO, USA) SAM (System Advisor Model) estimated the annual power generation for each study area section. The amount of energy was calculated based on the monthly electricity consumption of a four-person household provided by KEPCO. The annual energy self-sufficiency rate of the study area was estimated based on estimated power generation and consumption. Next, to calculate the energy self-sufficiency rate, the overall annual self-sufficiency rate was calculated by collecting actual power generation and power consumption data for each household. Finally, the results were analyzed by comparing the estimated and calculated self-sufficiency rates.

3.1. Energy Self-Sufficiency Rate Prediction

3.1.1. Consumption Prediction

The average electricity consumption per household in the study area was obtained from the electricity data development portal system provided by KEPCO. The power data development portal system standardizes various power usage information and provides power statistics, power usage patterns, and big data analysis information. The electricity consumption data of the study area were collected from the electricity data development portal system. The data were collected from January to December 2022 in Gangseo-gu, Busan based on the electricity consumption of 4 households, and calculated as the average electricity consumption per household by dividing it by the number of households to be collected. The data collected were based on electricity consumption per household, so it was multiplied by the number of households per building type and converted into monthly electricity consumption for each of the eight types.

3.1.2. Power Generation Prediction

- Typical Meteorological Year (TMY) data

TMY data are hourly meteorological data for one year created by selecting representative months of typical meteorological months that reflect the characteristics of continuously occurring weather based on a long-term meteorological database [35]. TMY data are widely used to evaluate the performances of energy systems, such as solar heating and photovoltaic systems, because they include various meteorological parameters like Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), dry-bulb temperature, and wind speed. The NREL officially distributes TMY data in the United States and provides TMY3 data worldwide. However, to secure accurate TMY data for the study area, the TMY3 data provided by The Korean Solar Energy Society (KSES) were used.

- System Advisor Model (SAM) program

The SAM program provided by the NREL was used to estimate the annual solar power generation in the study area. The factors entered when calculating solar power generation using the SAM were solar power generation system equipment data, weather data, and field data (Table 2). The model was designed to resemble the actual design conditions closely, and meteorological data from the KSES, specifically the TMY3 data for Busan, were used. To account for the variations in the number of panels, a model was designed to estimate the energy generation per building in eight distinct zones, and the annual energy generation was calculated.

There is a limitation in the system design of the program to estimate the generation. Therefore, separate simulations were performed for each building type. The PV panels installed in each building are fixed PVs and are designed to face both south and north. In addition, the orientation and tilt angle are different for each building type, so the simulation was performed with a system with more than one subarray. The power generation (P_{ac}) estimated through the simulation was calculated using the formula below (Table 3) [36]:

$$P_{ac} = \frac{P_{(ac,0)}}{(\mathrm{A}-\mathrm{B})} - \mathrm{C}(\mathrm{A}-\mathrm{B})(P_{dc}-\mathrm{B}) + \mathrm{C}(P_{dc}-\mathrm{B})^2 \quad (1)$$

Parameters used in the above formula:

$$\begin{aligned} \mathrm{A} &= P_{(dc,0)}\ 1 + C_1(V_{dc} - V_{dc,0}) \\ \mathrm{B} &= P_{(s,0)}\ 1 + C_2(V_{dc} - V_{dc,0}) \\ \mathrm{C} &= C_0\ 1 + C_3(V_{dc} - V_{dc,0}) \end{aligned} \quad (2)$$

Table 2. Input data list for predicting power generation.

Type			Data	Unit
Input	Facility parameters	PV	Capacity	kW
			Quantity	Numbers
			Size	mm
			Efficiency	%
			Inclination	°
			Azimuth	°
			Maximum power voltage	Vmp
			Maximum power current	Imp
			Open circuit voltage	Voc
			Short circuit current	Isc
		Inverter	Capacity	kW
			Quantity	Numbers
			Operating voltage	V
			Voltage rang	V
			Nominal AC voltage	Vac
			Nominal DC voltage	Vdc
			Maximum DC current	Adc
			MPPT voltage range	V
			Minimum MPPT DC voltage	Vdc
			Maximum MPPT DC voltage	Vdc
			Maximum DC voltage	Vdc
			Maximum DC current	Vdc
	Weather parameters		Dew point	°C
			Temperature	°C
			Pressure	hPa
			Wind direction	
			Wind speed	m/s
			DNI	Wh/m^2
			GHI	Wh/m^2
	Field parameters		Area	m^2
			Household	Numbers

Table 3. Definition of the parameters used in the power generation prediction formula.

Symbol	Description
P_{ac}	Gross ac output
$P_{(ac,0)}$	Maximum AC power
P_{dc}	Inverter DC input power
$P_{(dc,0)}$	Maximum DC power
C_0	Curvature between AC power and DC power W^{-1}
C_1	Coefficient of $P_{(dc,0)}$ variation with DC input voltage V^{-1}
C_2	Coefficient of power consumption during operation variation with DC input voltage V^{-1}
C_3	Coefficient of C_0 variation with DC input voltage V^{-1}

3.1.3. Energy Self-Sufficiency Prediction

The energy self-sufficiency rate can be calculated as long as you have data on electricity generation and consumption. Many studies [30,37–39] have calculated the energy self-sufficiency rate using a method similar to the formula below, but this study uses the energy self-sufficiency rate calculation formula used in Korea, considering that the study area is in Korea. The equation for calculating the energy self-sufficiency rate is as follows [40]:

$$\text{Energy Self} - \text{Sufficiency Rate}(\%) = \frac{\text{Energy Production}}{\text{Energy Consumption}} \times 100 \quad (3)$$

Energy production is influenced by the solar energy equipment and characteristic information, as well as the size, type, efficiency, installation angle, and direction of the module. On the other hand, the energy consumption is affected by thermal performance information such as thermal conductivity, thermal resistance, and pressure losses, among others. In this study, we focused solely on the electrical energy component of the energy consumption.

3.2. Energy Self-Sufficiency Rate Calculation

For the study area, data on power generation and consumption by households were collected for one year, from April 2022 to March 2023.

3.2.1. Consumption Calculation

Monthly consumption data for power reception (kWh), transmission (kWh), net load (kWh), cooling (kWh), and heating (kWh) were collected for 56 households. The data collected were the cumulative monthly consumption of each household, which were divided into monthly consumption. For comparison with the predicted consumption, the electricity consumption of all 56 households was summed up and divided by the number of households to obtain the average monthly electricity consumption per zone. To calculate the energy self-sufficiency rate for each of the eight zones, the electricity consumption of the households in each zone was summed up and divided by the number of households to obtain the average electricity consumption of the eight zones.

3.2.2. Power Generation Prediction

We gathered the daily generation data for each household, specifically representing the power generated by the photovoltaic system. Daily power generation was accumulated, converted into monthly power generation data, and organized into monthly power generation data for each of the 56 households. Power generation data of households corresponding to each type were collected to calculate the average monthly power generation for each type.

3.2.3. Energy Self-Sufficiency Calculation

The energy self-sufficiency rate of the study area was calculated using the actual energy consumption and energy generation data presented in Sections 3.2.1 and 3.2.2. The data were scaled to one household per year, one household per season, one household per month, and one household per zone.

4. Results

4.1. Energy Self-Sufficiency Rate Prediction

4.1.1. Energy Consumption

The average monthly household power consumption data were collected from the power data development portal system provided by KEPCO. Table 4 shows the results of a survey of the average monthly electricity consumption of households in Gangseo-gu, Busan, from January 2022 to December 2022. The average annual monthly electricity consumption for a four-person household in 2022 is 273 kWh. Based on the survey data, we used the monthly electricity consumption values as the energy consumption per household in the research area.

Table 4. Estimation of monthly average household consumption..

	January	February	March	April	May	June	July	August	September	October	November	December
APH *	273	274	242	254	233	241	299	383	331	252	244.	250

* Average power usage per household (kWh).

The average monthly household electric power consumption announced by KEPCO is listed in Table 4. The power consumption of each type was calculated by considering the number of households included in the eight types.

4.1.2. Energy Power Generation Prediction

The monthly power generation of each household was estimated, and the results are shown in Figure 4. Although they all have similar patterns, there are differences in the power generation depending on the installed capacity of each area's solar power generation system. Of the eight zones, A, C, D, E, and G have a relatively high generation capacity with 16 or 13 panels, respectively. B has similar conditions to C, but B's power generation is predicted to be half as low. B has one less panel than C, and there is also a difference in the placement of the PV panels. C tends to have more PV panels installed facing south than B. Therefore, the difference in power generation is likely due to the cumulative effect of the differences in panel quantity and orientation. F and f are areas with fewer PV panels per household compared to other areas, and have about half of the number of inverters compared to other areas. In particular, f is a multi-family building, so the lower generation was estimated by dividing the lower generation by the number of units compared to the other zones.

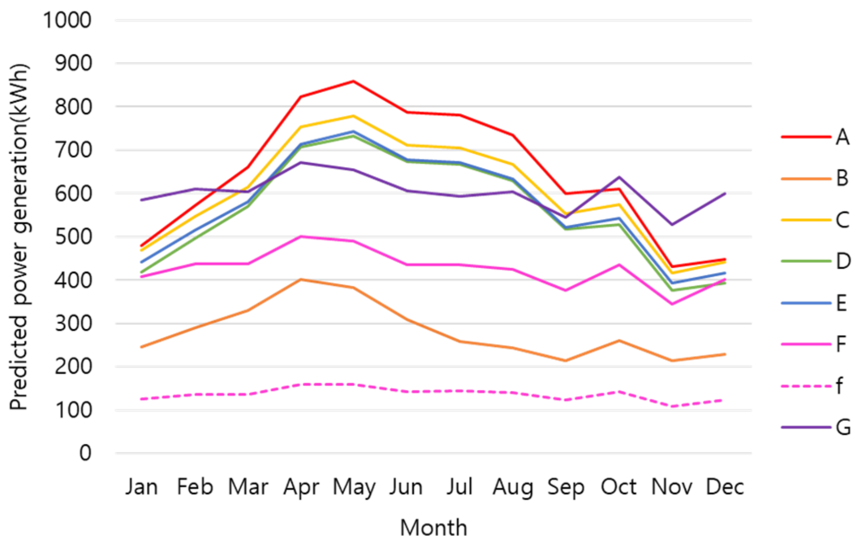


Figure 4. Monthly predicted power generation trends for each of the 8 districts.

4.1.3. Energy Self-Sufficiency Prediction

To estimate the energy self-sufficiency rate of the study area, the power generation and consumption data of 56 households were summed up and converted into total data. The converted data were used to estimate the monthly energy self-sufficiency rate of the study area (Figure 5). The results showed that the self-sufficiency rate was greater than 100% from January to December, and the annual self-reliance rate was 171%. In particular, the self-sufficiency rate was the highest at 250% in May, and the energy self-sufficiency rate was relatively low in August and September. This was analyzed by dividing the data into four seasons: spring, summer, fall, and winter (Figure 6). The amount of power generated by the PV system was higher than the amount consumed in all seasons. In the spring, when power generation was the highest and power consumption was the lowest, the highest self-reliance rate was 226%. In the summer, when the cooling power consumption was high, the self-sufficiency rate was 162%.

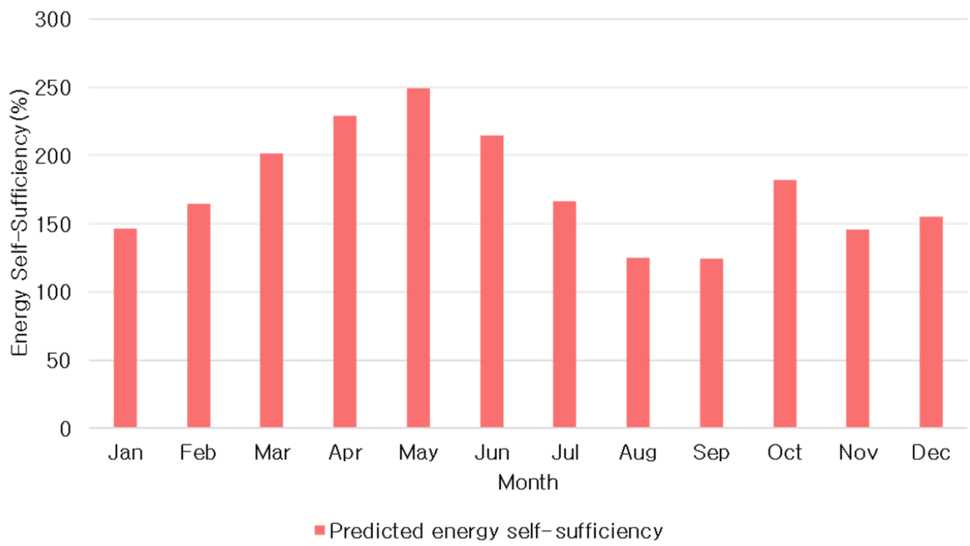


Figure 5. Annual predicted energy self-sufficiency rate progress.

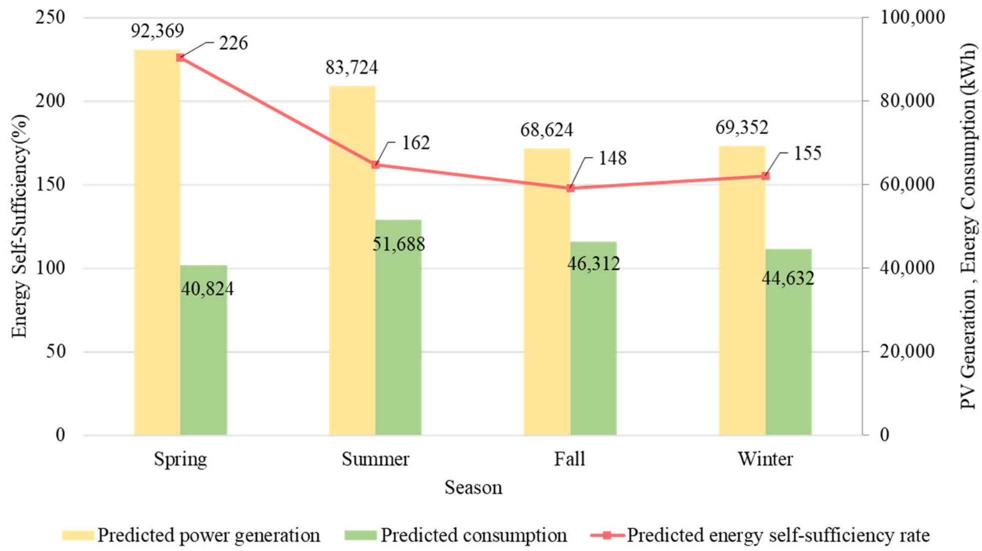


Figure 6. Trends of predicted power production, predicted energy consumption, and energy self-sufficiency rate by season.

4.2. Energy Self-Sufficiency Rate Calculation

4.2.1. Consumption Calculation

From April 2022 to March 2023, the monthly consumption data of 56 households (kWh), transmission (kWh), net load (kWh), cooling (kWh), heating (kWh), and power reception (kWh) were collected. The collected data included all electric energy consumptions, and the monthly average electricity consumption was calculated by adding the monthly consumption of all households and dividing it by the number of households (Table 5). The calculation results showed that the annual electricity consumption in the study area was 5416 kWh, with an average of 451 kWh of electricity consumed per month.

Table 5. Measurement of monthly average household consumption.

	January	February	March	April	May	June	July	August	September	October	November	December
APH *	497	445	445	399	422	432	457	488	454	454	434	490

* Average power usage per household (kWh).

As a result of analyzing the monthly consumption in each type, the electricity consumption was at a similar level in most types, except for type f, which had low power consumption owing to the smaller residential area for each household compared to the other types (Figure 7). In April, there was a sharp decrease in electricity consumption in area f, which was almost empty during the period due to maintenance and repair. Electricity consumption was higher in the summer and winter compared to the spring. This is due to the increased use of cooling power in summer and heating power in winter. In particular, electricity consumption was higher in the winter than in the summer, which is related to the characteristics of the study area where gas heating is not operated and it is windy, and the fact that there were many cold days compared to the average year during the study period, which led to a sharp increase in the heating electricity consumption.

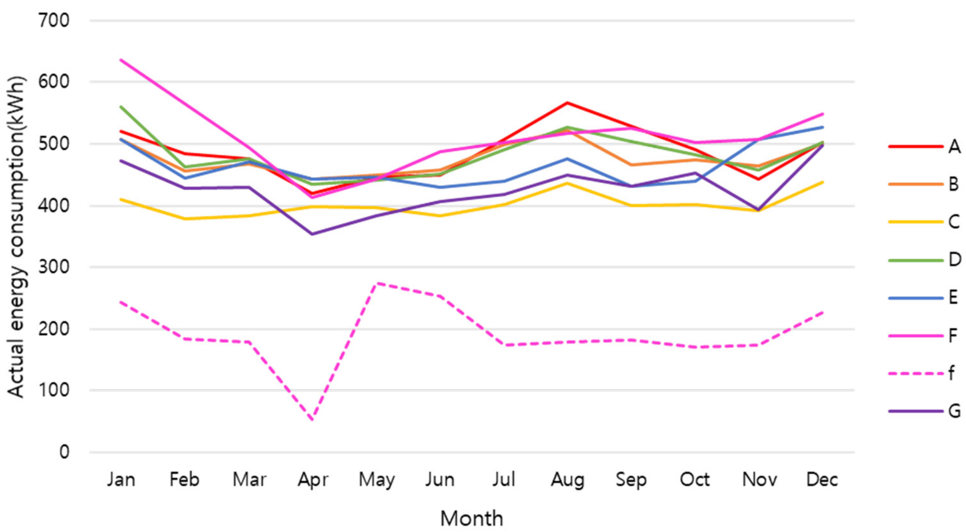


Figure 7. Monthly actual energy consumption trends for each of the 8 districts.

4.2.2. Power Generation Prediction

Data on the daily power generated by the PV systems of 56 households were collected from April 2022 to March 2023. Daily power generation data were accumulated, converted into monthly power generation data, and organized into monthly power generation data for each of the 56 households. In addition, the monthly average power generated by one household in each district was calculated by collecting the power generation data for the households corresponding to each district (Figure 8). The actual collected power generation was found to be proportional to the size of the installed PV system's facility capacity for each household. The average annual power generation in type A, with 16 panels per household, was 752 kWh. In type F, with 4.5 panels per household, the average annual power generation was the lowest at 140 kWh. The monthly power generation in all areas shows a similar pattern, and the April power generation in type f is low because in type f, two households live in one building with nine installed panels. Therefore, because the power generation in the building was divided into two households when calculating the power generation for each household, the power generation in type F was estimated to be half that of the other types. As with the consumption results, the PV system was not operational due to maintenance and repair, resulting in very low power generation in April.

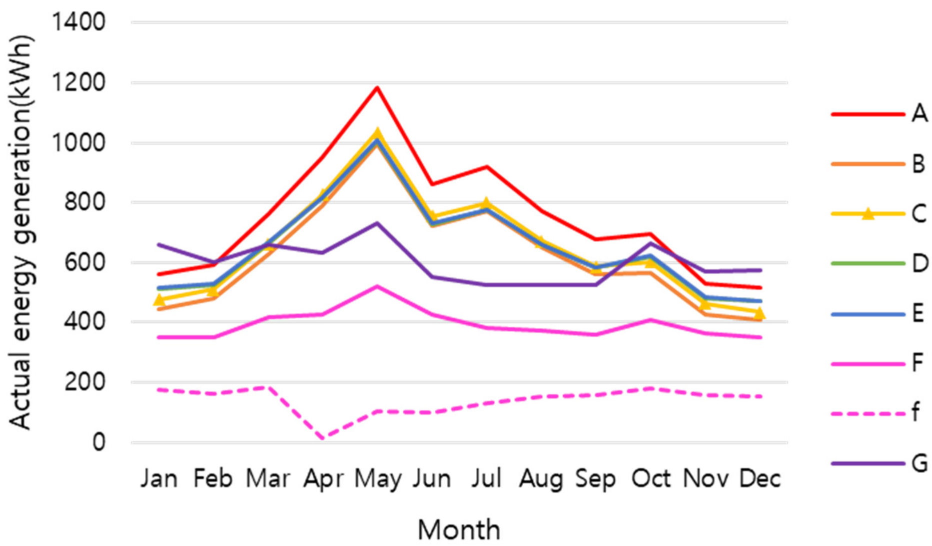


Figure 8. Monthly actual power generation trends for each of the 8 districts.

4.2.3. Energy Self-Sufficiency Calculation

The monthly electricity generation data and cumulative electricity consumption data of each household in the collected study area were summed up and converted into annual electricity generation and electricity consumption. Then, the energy independence rate was calculated by applying Equation (3). The results show that the self-sufficiency rate exceeded 100% from January to December, and the annual self-reliance rate was 133% (Figure 9). In particular, May showed the highest self-sufficiency rate of 211%, whereas December had a relatively low self-sufficiency rate of 92%. To conduct a detailed analysis of the underlying reasons for this, we divided the data into four seasons, and each affected self-sufficiency differently. We analyzed the data related to the PV system power generation and electricity consumption for each season (Figure 10). The energy self-sufficiency rate showed a gradually decreasing pattern, and the power generation from the PV system facilities in all seasons was higher than the electricity consumption. The spring, when power generation was the highest and power consumption was the lowest, showed the highest self-sufficiency rate at 177%, whereas the winter showed the highest sufficiency rate at 102%, as power generation and power consumption were similar.

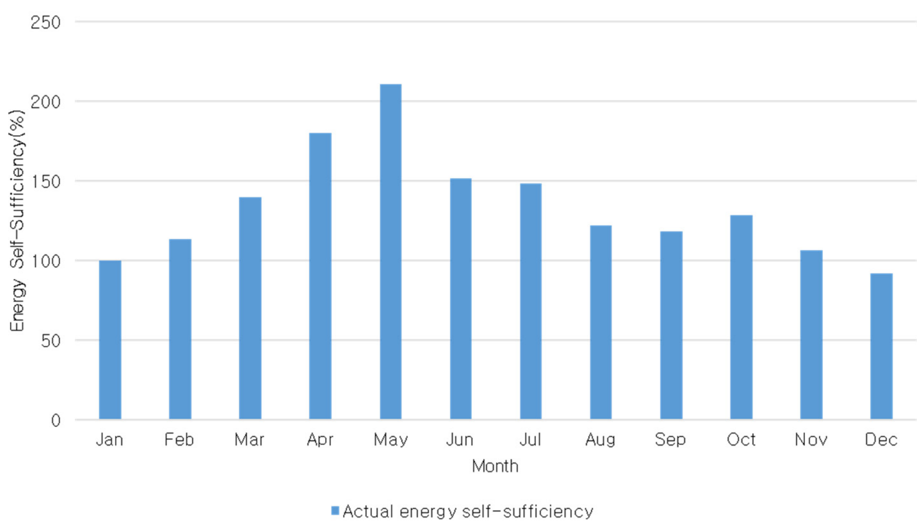


Figure 9. Annual actual energy self-sufficiency rate progress.

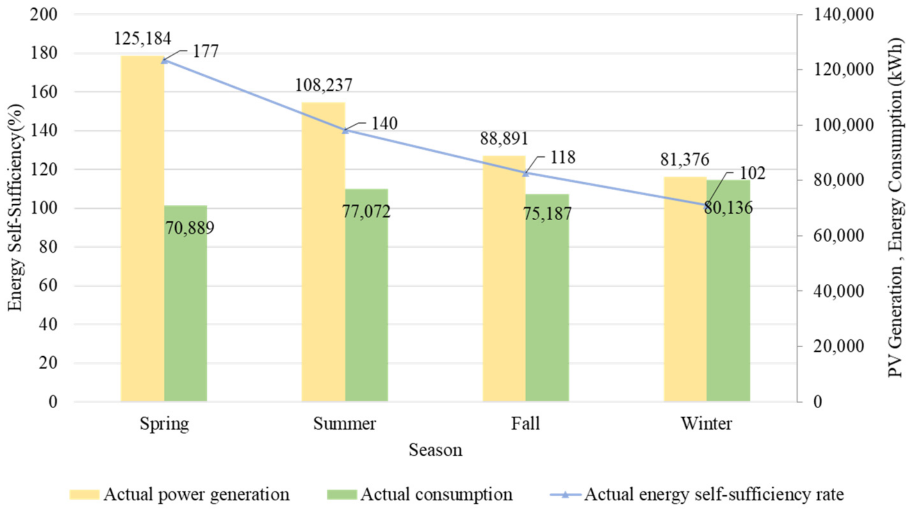


Figure 10. Trends of actual power production, actual energy consumption, and energy self-sufficiency rate by season.

5. Discussion

5.1. Comparison and Analysis of Predicted Energy Self-Sufficiency Rate and Actual Energy Self-Sufficiency Rate

The annual energy self-sufficiency rate estimated for the energy-sharing community of 56 households was compared with the actual energy self-sufficiency rate in the study area from April 2022 to March 2023 (Figure 11). The red line represents the estimated self-sufficiency rate, the blue line represents the measured (actual) self-sufficiency rate, and the gray line represents the ratio of the difference between these two values.

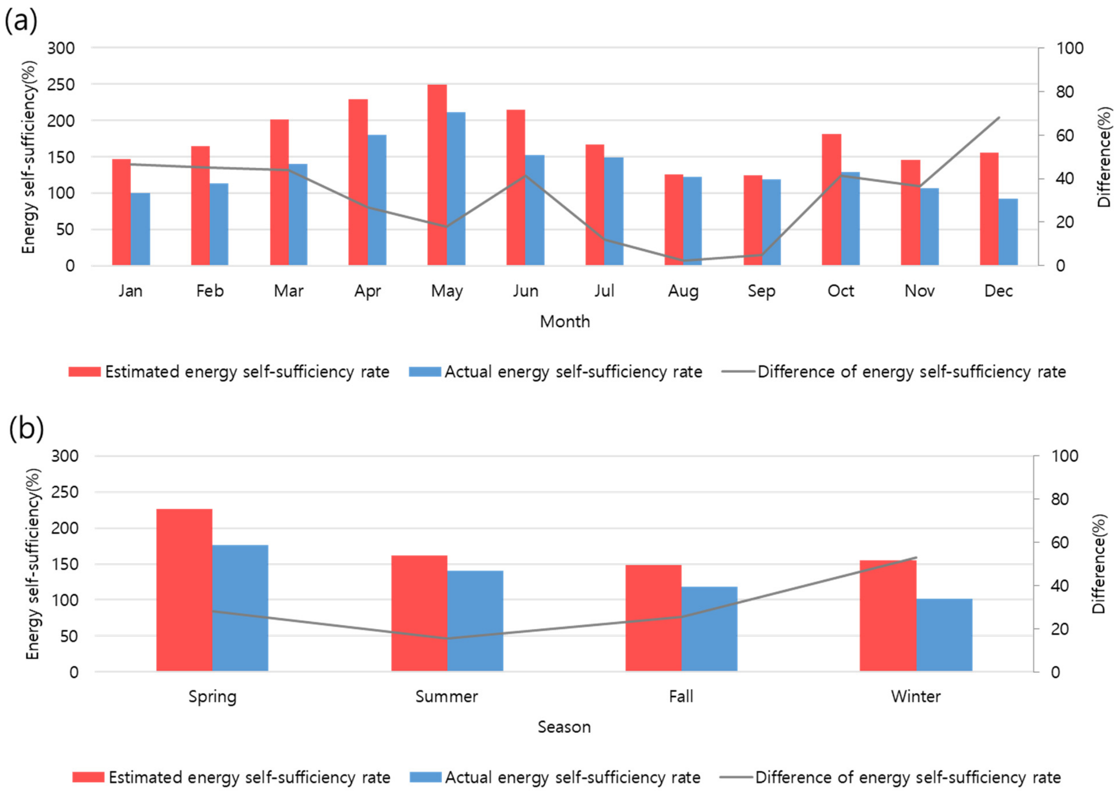


Figure 11. Estimated and actual self-sufficiency rate comparison graph: (**a**) monthly self-sufficiency rate and error comparison graph. (**b**) Seasonal self-reliance rate and error comparison graph based on monthly data.

The estimated self-sufficiency rate averaged 175% per year, while the actual self-sufficiency rate averaged 135% per year, resulting in a 28.57% error between the estimated and actual self-sufficiency rates. This is a higher error rate than the 20% we assumed earlier. When analyzing the monthly results integrated by season, it is evident that the self-sufficiency rate error during the winter is significantly higher than that during the summer. The cause of the error between the estimated and actual self-sufficiency rates can be determined through an analysis of the power generation and consumption (Figure 12). In the winter, when the error in the energy self-sufficiency rate is large, the difference in power generation is small, but the actual consumption is higher than the predicted consumption due to "electric" heating, which lowers the actual energy self-sufficiency rate. In the summer, not only is the difference in power generation small, but the difference in consumption is also small, resulting in an energy self-sufficiency rate. The error rate is also low.

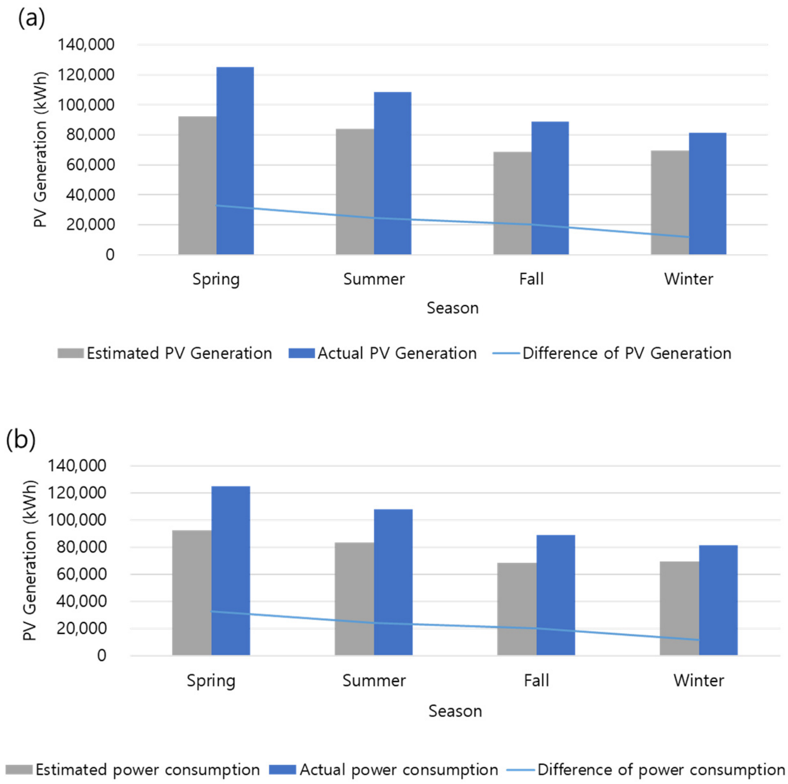


Figure 12. (**a**) Comparison of estimated and actual power generation and error graph. (**b**) Comparison of estimated and actual power consumption and error graph.

Furthermore, it is estimated that differences in the self-sufficiency rates occurred because of the differences between the TMY data used in the self-sufficiency rate estimation and actual weather conditions. To investigate this further, we compared the most significant factor of solar radiation between the TMY data and measured values for each. In Figure 13a, the orange color shows the insolation at TMY used to estimate power generation, where the yellow color shows the actual insolation during the study period. The navy blue color represents the error between the two. In Figure 13b, we can see that the error patterns of the energy independence estimates and the actual values are very similar, as well as the insolation error. Therefore, we can see that the correlation between the TMY used to estimate the power generation and the actual weather conditions affect the self-reliance error.

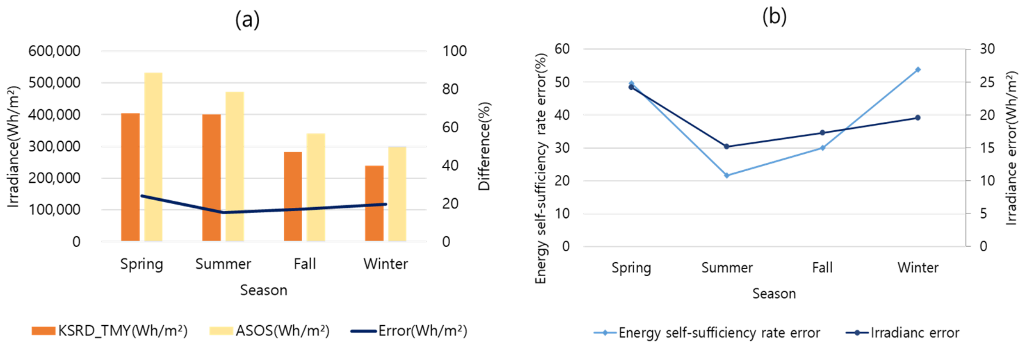


Figure 13. Graphs for comparison of insolation error and self-reliance error relationships: (**a**) TMY irradiance versus actual irradiance, and (**b**) TMY irradiance versus actual irradiance and energy self-sufficiency error patterns.

5.2. Comparison and Analysis of Energy Self-Sufficiency Rate by Type

There were two types of buildings in the study area: detached houses, where only one household lived in one building, and attached houses, where several households lived together in one building. In the case of a detached house, one household uses the electricity produced by the PV system installed on the rooftop. However, in the case of an attached house, because several households live together in one building, the generated electricity is divided according to the number of households. Therefore, we compared and analyzed the self-sufficiency rates according to house type (Table 6).

Table 6. Information by house type.

Building Type	A	D	E	F	B	C	F	G
Average area per household (m^2)	155	130	129	98	85	85	89	97
Pyeong	47	39	39	30	26	26	30	29
Number of panels	16	13	13	10	40	41	9	96
House type	Detached house				Attached house			
Average area per household (m^2)	128				77			
Pyeong	39				23			
Average number of panels per generation	13.75				13.29			

The estimated self-sufficiency rates for detached and attached house types were compared with the actual self-sufficiency rates (Figure 14). Based on this comparison, the annual average estimated self-sufficiency rate for detached houses was 207%, whereas the actual self-sufficiency rate for attached houses was 138% higher. The seasonal PV generation data showed that the PV generation amounts for detached and attached house types were similar; however, there were differences in the predicted PV generation amounts. Detached houses had higher generation amounts than the attached houses. The difference in the average number of panels per unit between the two types of units was approximately one panel, but when comparing seasonally, the differences in generation capacity accumulated. Therefore, it is likely that the lower predicted PV generation amounts for the attached house types were due to differences in the actual panel placements between the design and simulation. In terms of consumption, the predicted electricity consumption was the same for detached house types and attached house types. However, the actual electricity consumption was higher for detached house types than for attached house types. This is likely because detached houses have larger areas, leading to higher electricity usage for heating and cooling. Additionally, the predicted electricity consumption provided by

KEPCO may not have adequately accounted for the increased electronic device usage, which could have contributed to the difference in actual electricity consumption.

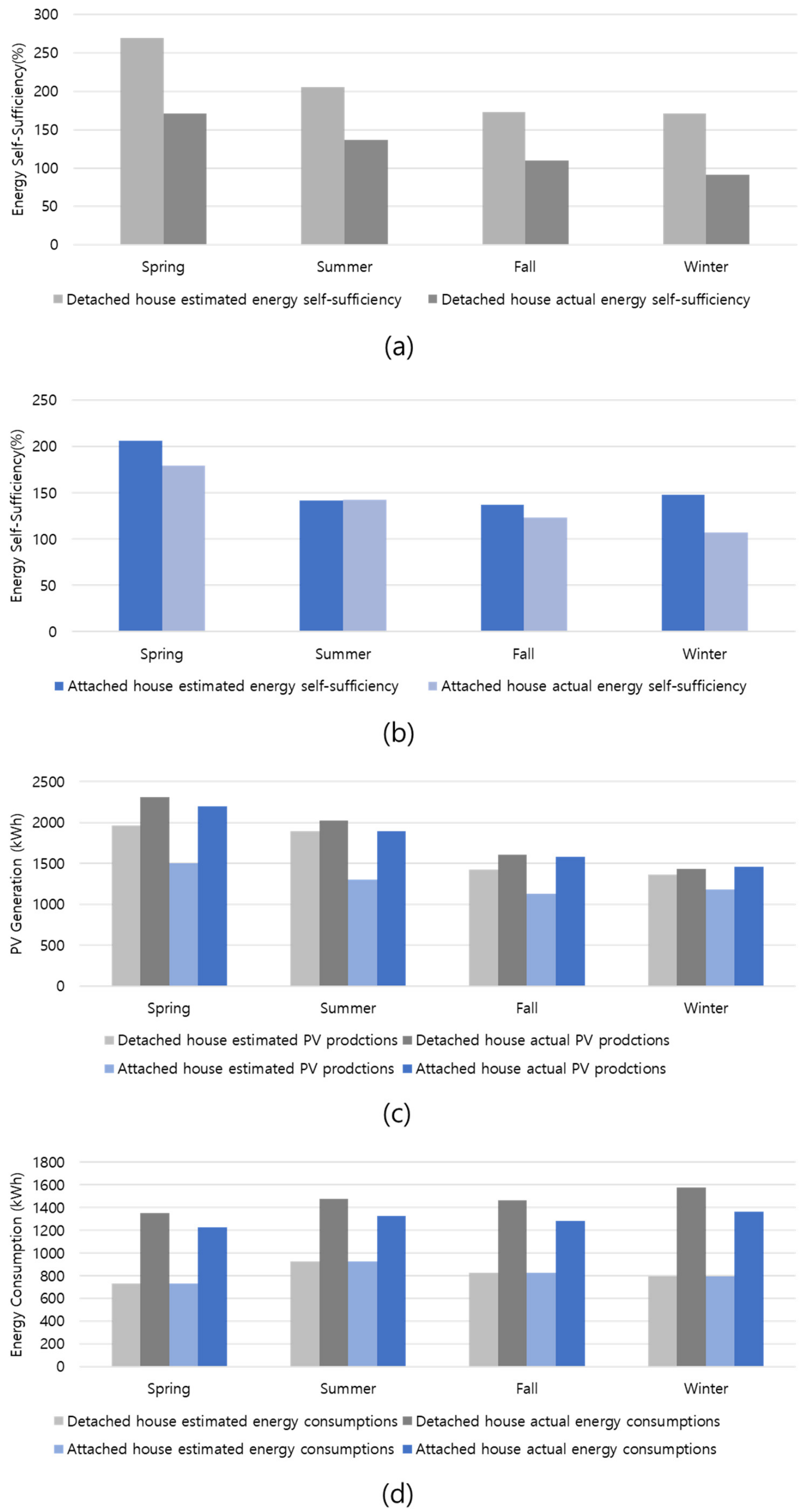


Figure 14. Comparison graph according to season. (**a**) Graph of estimated energy self-sufficiency rate and actual energy self-sufficiency rate in detached house type. (**b**) Graph of estimated energy self-sufficiency rate and actual energy self-sufficiency rate in attached house type. (**c**) Graph of estimated PV generation and actual PV generation in detached and attached house types. (**d**) Graph of estimated energy consumption and actual energy consumption in detached and attached house types.

5.3. Power Consumption Correction

To reduce the error between the average power consumption and actual power consumption, the power consumption was corrected by applying a correction coefficient. The correction coefficient was performed in 0.1 increments from 1.1 to 1.9, and the errors between power consumption before and after the correction and actual consumption were compared using MAE and RMSE (Figure 15). In all cases, the MAE and RMSE showed improved values after correction compared to those before correction. In the summer, when the error between the average and actual power consumption values was small, the correction coefficient value was small, and the difference between the MAE and RMSE before and after the correction was also small. On the other hand, in the winter, when the actual power consumption was higher than the average power consumption owing to the characteristics of the study area where heating was used only as electric power, after correction, the MAE was 50.0% and the RMSE was 63.3% for detached house type, and the MAE was 51.2% and the RMSE was 60.3% for the attached house type. This suggests that the correction factors helped improve the accuracy of the electricity consumption predictions during the winter.

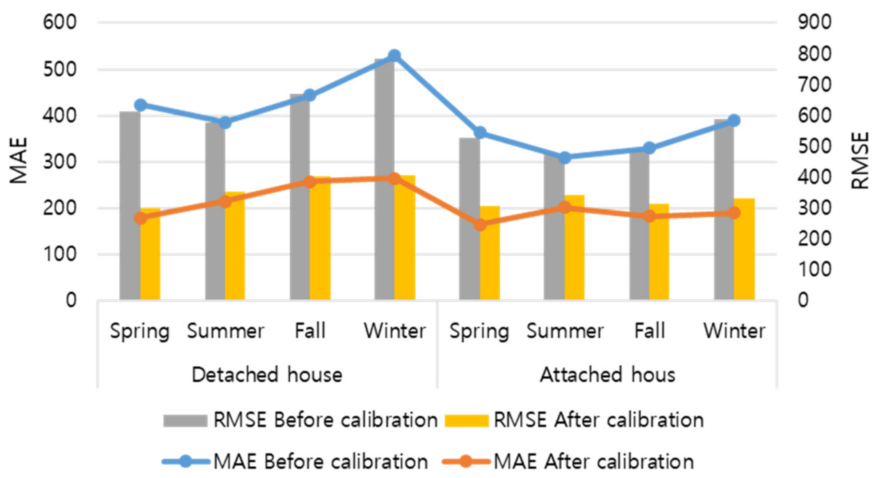


Figure 15. Seasonal forecast power generation and forecast consumption.

6. Conclusions

This study has provided valuable insights into estimating and calculating energy self-sufficiency rates within energy-sharing communities, showcasing the interplay of various influencing factors. The energy self-sufficiency rate was estimated by focusing on an energy-sharing community of 56 households and comparing it to the actual energy self-sufficiency rate. The 56 households were divided into eight types according to the facilities, capacity of the PV system, annual energy self-sufficiency rate achieved using facility conditions, TMY, estimated power generation for each type, and average monthly power consumption data for four people provided by KEPCO to estimate the annual energy self-sufficiency rates for each type. The actual energy self-sufficiency rates were calculated using actual power generation and power consumption data in the study area from April 2022 to March 2023. Comparing the annualized energy independence rate, the estimated energy independence rate (171%) was calculated to be 28.57% higher than the actual energy independence rate (133%), which is a larger error than the assumption of a 20% error between the estimated and actual values. An additional seasonal analysis revealed that the error between the estimated and actual self-sufficiency rates is significantly larger in summer than in the winter. An analysis of energy generation and consumption sheds light on the reasons for this discrepancy. In winter, when the self-sufficiency rates were higher, the difference in energy generation was relatively small. However, because of electric heating, the actual energy consumption exceeded the predicted consumption, leading to a lower self-sufficiency rate. Furthermore, by comparing the difference in solar radiation levels between the TMY data, which are generally used to estimate the power generation of PV systems and actual weather conditions, it was confirmed that the correlation between the difference in weather conditions and the energy self-sufficiency rate error was similar. This suggests that variations in weather conditions can contribute to differences in self-sufficiency rate calculations.

Additionally, this study divided residential types into detached and attached housing types and compared the energy self-sufficiency rates by type. The difference in PV system panels installed in each type of building was relatively small, by approximately one panel, but when compared to annual power generation, the differences accumulated, resulting in a lower predicted generation for the attached house type. In the case of electricity consumption, the area of the detached house type is larger than that of the attached house type; therefore, there is a large amount of electricity used for cooling and heating, resulting in a large error. KEPCO's average monthly electricity consumption (273 kWh) was based on four people, which was calculated for a fixed number of people in each household, as compared to the actual measured power (430 kWh). A difference in the consumption of 157 kWh was observed. The significant difference in power consumption between the detached and attached housing types can be attributed to variations in the number of occupants and the size of each dwelling. It was observed that the detached housing type has approximately 1.7 times more floor area than the attached housing type, leading to higher energy consumption for heating and cooling. To reduce power consumption errors, the power consumption values were corrected using the correlation between the actual power consumption and power consumption per household provided by KEPCO. A seasonal analysis of the corrected values showed notable reductions in the MAE (by 50.5%) and RMSE (by 61.5%) during the winter months, aligning with the energy consumption patterns of the research area, which rely on electric heating.

In this study, the energy self-sufficiency rate was calculated for the electricity production and consumption in the study area, and in the power consumption correction process, and only the correlation between the actual power consumption and the electricity consumption data per household provided by the KEPCO was used. Through this, it was confirmed that the existing electricity consumption was underestimated. An underestimation of electricity consumption can lead to an overestimation of the effectiveness of energy self-sufficiency, and resources may not be available to meet actual needs in the future. It can also distort targets for sustainable energy management, which can lead to instability in long-term energy planning. Therefore, it is necessary to collect more accurate and sufficient electricity consumption data in the future. On the other hand, this study did not consider energy consumption other than electricity, so in the future, it is necessary to calculate the energy self-sufficiency rate including all energy used other than electricity, such as gas and water for heating, and to consider additional variables that are highly correlated with electricity consumption, such as the number of people and area, to improve energy consumption estimation.

This study compared and analyzed the energy self-sufficiency rate estimated in the design phase and the actual energy self-sufficiency rate in the operation phase by selecting a national pilot smart city as a research area. Until now, there has been a lack of studies comparing the estimated energy independence rate of smart cities with the actual value. The error between the estimated value and the actual value can contribute to improving smart city design models and minimizing negative impacts on energy efficiency by considering problems such as errors caused by insolation and the overestimation of consumption when planning smart cities in the future. The comparison of energy self-sufficiency rates in smart cities is expected to provide symbolic meaning for sustainable city building, policy formulation, and field experience in a broader sense. In addition, it is expected that a large amount of data will be available after the operational phase of the study area is developed in the future to enable quality research.

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