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Energy Analysis of a Net-Zero Energy Building Based on Long-Term Measured Data: A Case Study in South Korea

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Abstract: In this study, the energy consumption and generation characteristics, the operation status of a photovoltaic (PV) system, and the energy balance of a net-zero energy building (nZEB) in South Korea were analyzed based on the data collected over a 10-year period (2012–2021). The average annual power consumption of the nZEB was 101.3 MWh, 6.2% higher than the estimated power consumption. The PV system of the nZEB had an annual power generation capacity of 105.8 MWh, indicating an increase of 10.6% compared to the estimated value. The failure of PV systems such as module cracks, inverter failures, and performance degradation led to a decrease of 21.5% in the power generation. Energy balance analysis was conducted by comparing the energy consumption and generation data based on yearly, monthly, daily, and hourly time intervals. In addition, load coverage factor (LCF) and supply coverage factor (SCF) were used to evaluate the load matching rate. The nZEB achieved a net-zero energy status for 5 out of the 7 years of normal operation (2012–2018) based on average annual data. However, the energy balance analysis using hourly measured data showed that there was both a surplus and a shortage of power every year, and that the average annual power surplus and shortage were 56.4 MWh and 54.3 MWh, respectively. In addition, the load matching analysis showed that the annual LCF and SCF were approximately 0.36 and 0.32, respectively. Thus, the advanced nZEB design, hourly data-based energy analysis, fault diagnosis and maintenance, and the strategies enhancing the self-consumption rate should be considered to expand nZEB dissemination.

Keywords: net-zero energy building; energy analysis; energy consumption; energy generation; photovoltaic system; long-term operation

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1. Introduction

To address global warming, the United Nations Intergovernmental Panel on Climate Change (IPCC) states that to limit the global average temperature rise to 1.5 °C, the global carbon dioxide (CO_2) emissions must be reduced by at least 45% by 2030, compared to the levels noted for 2010, and carbon neutrality must be achieved by 2050 [1]. Accordingly, several international efforts are being executed to lower carbon emissions. One of the strategies being considered in the building sector is the implementation of zero-energy buildings (ZEBs), which apply high-efficiency active and passive technologies. These technologies include renewable energy systems, high-efficiency equipment, and high-performance building materials. In addition, since approximately 36% of global energy consumption is used for buildings [2], the ZEBs are more promising for saving energy. Hence, global organizations, including the International Energy Agency, and advanced countries worldwide are promoting various support measures and regulations to promote and expand the dissemination of ZEBs [3–9]. A net-zero energy building (nZEB) is defined as a building that minimizes the energy load required for its operation and meets its own energy requirement using renewable sources, thereby eliminating the use of external energy [10]. To enhance the dissemination of such buildings, diverse studies on the design, construction, demonstration, and evaluation of ZEBs have been conducted worldwide over the past two decades [11–14]. Although several studies on simulation-based ZEB design and performance evaluation have been conducted previously [15–17], a thorough evaluation that is based on actual measured data is crucial to ascertain the achievement of net-zero energy and assess operational performance [18].

Anderson [19] conducted a case study on the energy performance evaluation of an nZEB by considering a research center building within a university campus in Australia. This energy center was designed and constructed to achieve net-zero energy, with an annual power consumption of 148 MWh and generation of 197 MWh using a photovoltaic (PV) system with a power generation capacity of 163 kWp. An empirical analysis confirmed that the amount of generated energy exceeded that of consumed energy. Lim et al. [20] empirically evaluated the energy balance of a ZEB, which was an educational research building in South Korea. They analyzed a year's worth of measured data and revealed that the building consumed 14.4 MWh of electricity, while the PV system generated 36.7 MWh, resulting in an energy surplus of approximately 22.3 MWh. The study also identified an energy cost-saving effect of approximately 8135 won/m^2 based on the building's annual power consumption per unit area. Thomas and Duffy [21] conducted an energy performance analysis of zero-energy homes in New England based on the data collected over 12 months; the analysis revealed that out of the ten homes considered in the study, six achieved net-zero or surplus energy. Additionally, when compared with the power consumption of the buildings predicted at the design stage through simulation and the PV-generated power, the actual power consumption was 14% lower than the predicted value, and the power generation displayed a variance of $\pm$10%. Based on the measured data, the authors highlighted the importance of considering energy efficiency in ZEB design, noting the potential to minimize the scale of renewable energy systems by reducing energy consumption. Heinze and Voss [22] analyzed the energy characteristics of 20 ZEBs in Freiburg, Germany. The juxtaposition of their energy consumption and generation data revealed that 15 out of the 20 buildings considered in the study generated surplus energy, consuming an average of 79 kWh/m^{2}a and producing an average of 115 kWh/m^{2}a, indicating an average surplus energy of 36 kWh/m^{2}a. Li et al. [23] conducted a feasibility test for two projects related to nZEBs in specific regions of China that experience hot summers and cold winters. Compared with regular buildings, the application of high-efficiency and eco-friendly passive and active technologies to implement ZEBs resulted in a 47% reduction in the total power consumption; the energy balance analysis results indicated that due to PV-generated power, the annual power consumption of the two projects reduced to 29 kWh/m^{2}a and 33.4 kWh/m^{2}a, respectively. However, the reduction was not enough to achieve net-zero energy. The authors suggested that it is better to achieve net-zero energy by considering the energy consumption and generation characteristics at the community level. Kim et al. [24] analyzed the energy consumption and generation characteristics of the Seoul Energy Dream Center, a ZEB located in Seoul (South Korea), using the data measured in 2020. The building minimized its heating and cooling energy consumption by applying passive and active technology elements, achieving zero energy using renewable energy facilities, including PV systems and geothermal heat pumps. Over the course of a year, the building's power consumption and generation were 165,676 kWh and 342,977 kWh, respectively, thus generating surplus energy from the annual energy balance perspective. Furthermore, the load matching of energy consumption and generation carried out based on the data collection time interval indicated that the smaller the time interval, the greater the difference between the load cover factor and supply cover factor. Thus, Kim et al. [24] noted that annual energy balance analysis could not clearly reflect the energy consumption and generation characteristics of nZEBs; therefore, they suggested that energy performance should be evaluated based on a data collection time interval of at least 1 h. Nikdel et al. [25]

analyzed the energy consumption and generation characteristics of six all-electric net-zero energy houses in Texas, the United States of America, using the data measured over the course of 22 months. Their results revealed that half of the buildings achieved net-zero energy, and building energy consumption was generally underestimated. Further analysis of monthly, daily, and hourly data portrayed a progressive decrease in the net-zero energy compliance. Dermentzis et al. [26] conducted a four-year energy analysis on two net-zero energy multi-family buildings in Austria. The results revealed that the energy consumption of the buildings exceeded the energy generated by their PV system by 27–39%, preventing the attainment of zero energy status. The authors attributed this limitation to the low efficiency of the passive and active technologies, while highlighting the necessity of minimizing heat loss and auxiliary energy consumption for successful nZEB compliance.

While numerous studies related to the design, operation, and performance evaluation of ZEBs have been carried out with the aim of expanding their distribution, there is a lack of studies evaluating their energy balance and operational characteristics based on extensive long-term operation data to ensure their practical effectiveness. Notably, a report on the operational status of ZEBs released by the Ministry of Land, Infrastructure, and Transport of South Korea highlights this issue. A 2022 survey on the monitoring status of energy production and consumption across 50 ZEBs revealed that approximately 80% (38 ZEBs) were not adequately monitored and recorded for energy data. This oversight makes it difficult to ascertain their operational status and renders the verification and enhancement of their effectiveness impossible. To address the issues from the literature review, long-term (10 years) operation data for the nZEB were analyzed in this study to assess its practical effectiveness in terms of the operation characteristics and energy performance. Based on the operation data of 2012–2021, energy consumption and production for the nZEB located in South Korea were characterized. In addition, a comprehensive analysis of the long-term operational status of the PV system, which is the most widely used energy generation system for the nZEBs, was conducted. Furthermore, the energy balance analysis for the nZEB was performed based on different measuring time intervals to scrutinize the patterns of energy surplus and shortage and the load matching rates.

2. Overview of the Net-Zero Energy Building Analyzed in this Study

The Global Environment Research (GER) building was used as an nZEB within the National Institute of Environmental Research (NIER) located in Incheon (South Korea). The GER building spans a total floor area of 2449.2 m^2, distributed over one underground and two aboveground floors. The underground level accommodated spaces designated for utility and facilities (including machinery, electricity, generator, and elevator machine rooms), as well as hallways, and did not have a heating and cooling space. The first floor, which was intermittently heated or cooled, housed the main hall, exhibition spaces, international conference halls, information and situation rooms, airlock rooms, and restrooms. The second floor, which was primarily used by employees, contained offices, meeting rooms, and restrooms. With the exception of the meeting rooms, the entire floor was continuously managed by the heating, ventilation, and air conditioning (HVAC) system. The building's HVAC system covered the following areas: a combined heating and cooling area of 1677.9 m^2, a heating-only area of 45.3 m^2, and a non-heating or cooling area of 26.0 m^2. Designed for an nZEB, the building was equipped to reduce its power consumption to 49.5 kWh/m^{2}a (from the standard building energy consumption of 123.8 kWh/m^{2}a) by applying active and passive technologies and substituting the power supply with solar energy. It was constructed as south-facing and had a square shape to minimize heat loss from the envelope and maximize PV module installation. The space heating, space cooling, and domestic hot water systems included geothermal heat pumps, solar thermal collectors, and hot- and cold-water storage tanks. It was constructed as an all-electric building, using only electricity for its final energy consumption for building operation. The snapshot shown in Figure 1a portrays the exterior of the building, and Figure 1b illustrates the spatial compositions and heating or cooling patterns on the first and second floors.

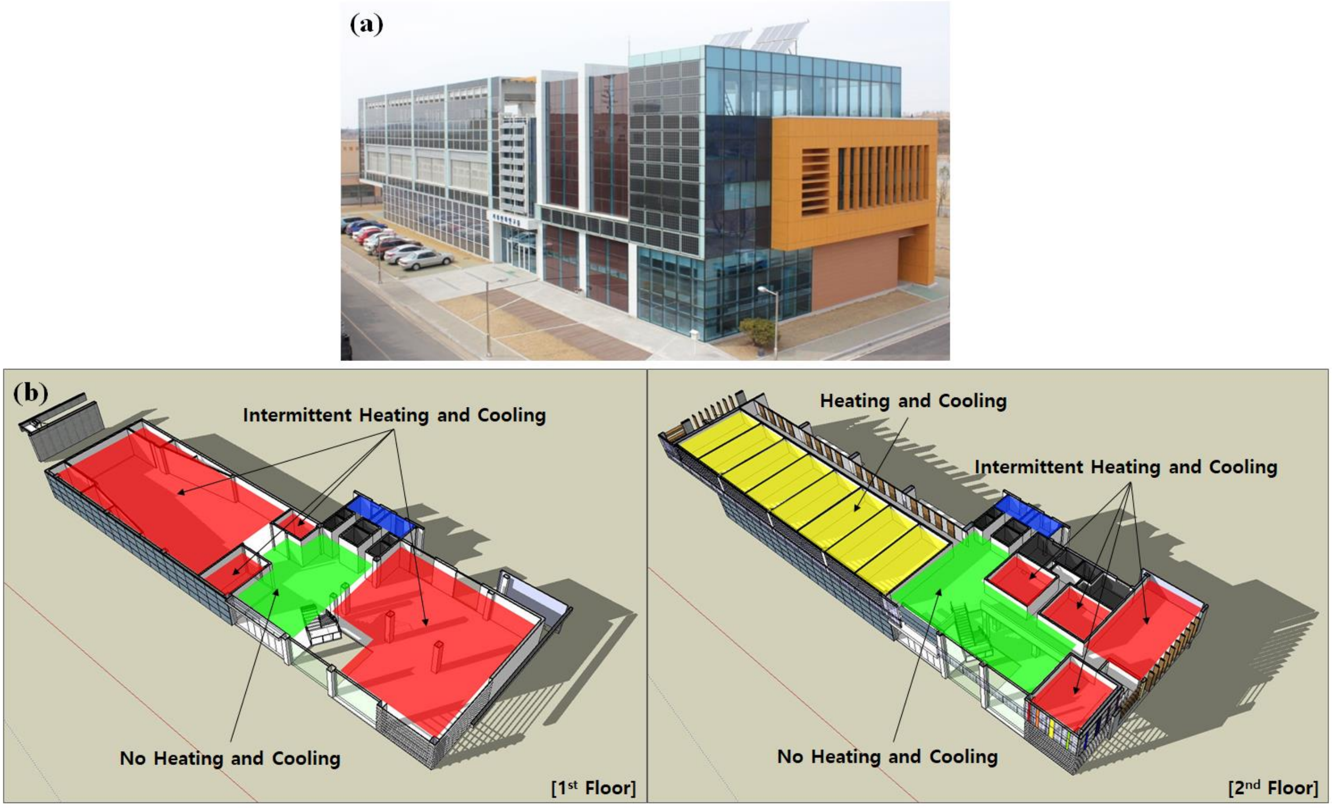
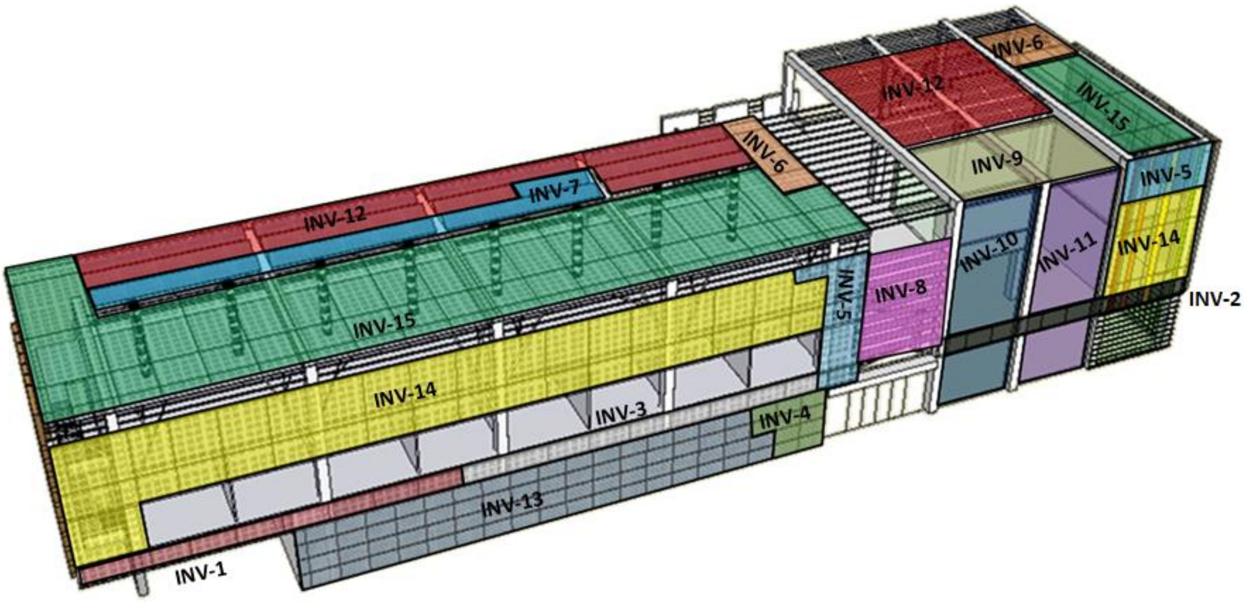


Figure 1. (**a**) Exterior of the Global Environment Research (GER) building; (**b**) spatial compositions and heating and cooling patterns of the first and second floors.

Figure 2 illustrates the solar power generation system in the GER building including PV module type, installation location, tilt angle, total capacity of each module type, and inverter capacity. Notably, building integrated photovoltaic modules were installed on all south-facing surfaces and the rooftop, excluding certain structural and window areas. The rooftop also housed horizontal and inclined PV modules, arranged in a pergola setup. The solar system, spread over an area of 1177.9 m^2, comprised 871 PV modules of five types (four polycrystalline and one amorphous), with a total generation capacity of 116.2 kWp. These modules were organized into 15 groups (each connected to an inverter) based on their type, location, and capacity for efficient power generation.

To monitor the power consumption and generation status of the GER building and analyze its net-zero energy performance, a data monitoring and storage system was installed, as illustrated in Figure 3. To understand the building's power consumption characteristics, the power meters were installed to measure the total and unit power consumptions of the offices, meeting, public relations (PR), and machine rooms, and other areas in the building. For analyzing the power consumption by source, 143 power consumption data points were set, including lights, electric heaters, fan coil units, and so on. The power consumptions for the facilities of the machine rooms such as the geothermal heat pumps, various circulation pumps, and so on, were measured separately. To assess the power generation characteristics of the GER building, the amount of electricity produced from the PV systems installed in the building was measured. The power generation performances of individual PV module arrays were analyzed by connecting the power monitoring module buses to 15 PV inverters (to collect the data from each module), and a power meter was installed in the transformer panel, where the power output from the inverters was gathered, to measure the total amount of generated electricity. Additionally, irradiance sensors, thermometers, and hygrometers were installed to measure the environmental information. The sensors for measuring the energy production and consumption of the GER building were connected to an integrated monitoring system, allowing for real-time data monitoring and collection.



Inverter Number	Module Type	Tilt Angle (°)	Module Capacity (Wp)	Module Quantity (ea)	Total Area (m^2)	Total Capacity (kWp)	Inverter Capacity (kWp)
INV_1	GtoT	90	171	12	22.08	2.052	3
INV_2		90	171	12	22.08	2.052	3
INV_3		90	171	13	23.92	2.223	3
INV_4		90	213	10	17.7	2.13	3
INV_5	GtoG	90	145	18	25.38	2.61	3
INV_6		0	145	18	25.38	2.61	3
INV_7	GtoT	30	145	16	22.56	2.32	3
INV_8		Tracking	43	32	16.96	1.376	3
INV_9	Amorphous	0	50	32	29.76	1.6	3
INV_10		90	50	52	48.36	2.6	3
INV_11		90	50	52	48.36	2.6	3
INV_12	GtoT	30	145	70	98.7	10.15	11
INV_13	GtoT	90	213	66	116.82	14.058	15
INV_14	GtoG	90	145	160	225.6	23.2	25
INV_15		0	145	308	434.28	44.66	45
Total	-	-	-	871	1177.94	116.241	129

Figure 2. Layout of the photovoltaic (PV) systems installed in the Global Environment Research building and their specifications.

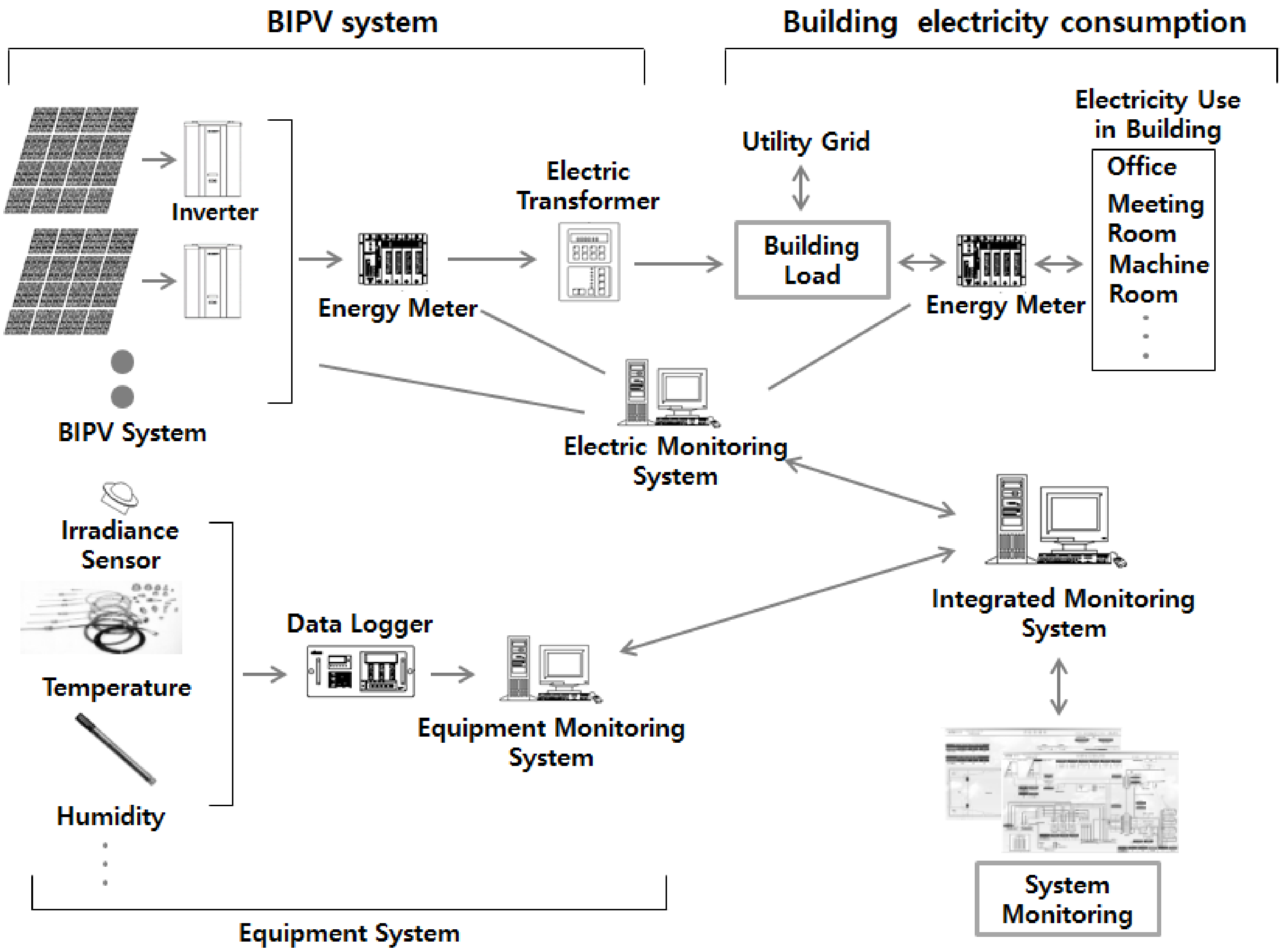


Figure 3. Schematic of the data monitoring and storage system.

3. Results and Discussion

3.1. Energy Consumption Characteristics

The energy consumption characteristics of the GER building were analyzed using the electrical power consumption data measured from 2012 to 2021. In addition, the characteristics of the energy consumption measured were compared with those estimated at the design phase. A VisualDOE 4.0 developed by Lawrence Berkeley National Laboratory was used to estimate energy demand and consumption of the GER building to achieve the nZEB. Building modeling based on the drawings was performed, and input information such as energy-related equipment, weather, and operations was used for the simulation. The weather information was set by using 30 years of average data released from Korea Meteorological Administration. The building operation information, such as the lighting and equipment densities, their usage patterns, population density, working schedule, and so on, were determined by analyzing the operation data of the building similar to the scale and purpose of the designed building. In addition, the ventilation rates were set by the regulations for the building equipment standard in South Korea. Figure 4 illustrates the variations in annual cumulative power consumption. During this period, power consumption ranged from 83.7 MWh to 106.3 MWh, with an average annual cumulative power consumption of 98.5 MWh. Since 2020, a decreasing trend in annual power consumption has been noted, owing to a reduction in the number of workers and shortened operating hours amid the COVID-19 pandemic. Separate analyses of the average annual power consumption for 2012–2019 and 2020–2021 portrayed annual average power consumptions of approximately 101.3 MWh and 87.3 MWh, respectively, indicating a decrease of 13.9% due to the COVID-19 pandemic. The annual power consumption during 2012–2019 increased by 6.2% when compared to the anticipated annual power consumption (95.4 MWh) during the design phase. This increase could be attributed to the installation of monitoring servers and PR equipment and an increase in the use of individual electrical devices. In addition, during the COVID-19 pandemic, the annual power consumption was 8.5% less than the anticipated annual power consumption during the design phase. Notably, in 2020, the first year of the COVID-19 outbreak, the annual power consumption was lower by 12.2% than the estimated annual power consumption.

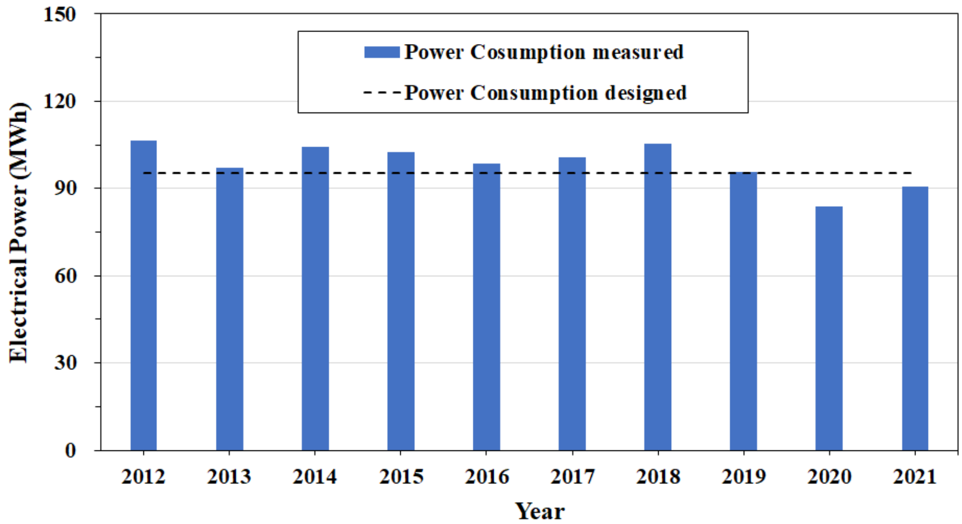


Figure 4. Annual cumulative power consumptions for 2012–2019.

Figure 5 juxtaposes the average monthly power consumption for 2012–2019 (blue bar graphs) and 2020–2021 (orange bar graphs) recorded during the period before and after the COVID-19 outbreak. The monthly power consumption ranged from 4.7 MWh to 13.6 MWh, with higher power consumption being noted in winter and summer (due to heating and cooling loads, respectively) compared to that in spring and fall. Due to the climatic characteristics of South Korea, the power consumption for heating was the highest in the cold winter months (December–February), peaking in January (at approximately 12.2 MWh); this was followed by the power consumption in summer (July–August) (due to the higher cooling load). In the early spring (March) and late fall (November) periods, the monthly power consumption was relatively high, owing to the requirement of heating during these transition months. Tracing the average monthly power consumption trends in the pre- and post-pandemic periods portrayed a similar power consumption pattern, with the monthly power consumption reduction ranging from 2.2% to 22.7% depending on the extent of group activity restrictions levied during the pandemic based on the number of confirmed COVID-19 cases.

Figure 6 presents a stacked bar graph that delineates the power consumption by source over the course of 10 years, segmented into electrical equipment, lighting, space heating, space cooling, ventilation, and water heating. From 2012 to 2019, prior to the COVID-19 outbreak, the consumption hierarchy, in descending order, was as follows: electrical equipment, space heating, lighting, space cooling, ventilation, and water heating. This pattern remained consistent annually. The largest share was claimed by electrical equipment (at 57.0%), a reflection of the GER building's extensive and prolonged use of various electrical apparatuses. Due to the long period and cold weather in winter, space heating accounted for 23.3% of the total power consumption. Building lighting and cooling (during summer) accounted for 7.6% and 7.5%, respectively. Ventilation required 3.8% of the total power consumption, and hot water production for heating required the least energy (at 0.9%). In 2020 and 2021 (during the COVID-19 pandemic), a notable dip in the usage of electrical devices and space lighting was recorded, 19.7% and 24.3%, respectively, due to the reduced workforce in the building. This resulted in an increased proportion of electrical power consumptions for space heating and space cooling. When juxtaposed with the anticipated consumption of the building during the design phase, we observed a surge in the electrical equipment's power usage. This uptick could be attributed to the installation of monitoring servers, PR facilities, and individual electrical devices. Concurrently, an underestimation in the circulating pump's consumption led to a significant hike in the actual power required for cooling and heating. Contrastingly, the consumption for lighting plummeted markedly, which could be attributed to the continual shutdown of the lighting of the first floor and basement, along with the predominant use of localized office lighting. Additionally, a considerable reduction in ventilation power consumption was noted when compared with the value estimated at the design phase. This is because the design for the ventilation system was conducted based on architectural standards, which is different from the real operation of the ventilation system. This analysis highlights the substantial impact of actual facility operation and building occupancy characteristics on the overall power consumption metrics, emphasizing the importance of incorporating building operational characteristics when designing nZEBs. Therefore, there is a compelling need to address the disparity between the designed and measured values. This can be achieved by conducting thorough evaluations of the efficacies of different nZEB designs while leveraging the energy data monitoring systems and extensive measurement data for a meticulous analysis of energy operational status, and subsequently integrating the findings to determine the optimal methodology to design effective nZEBs.

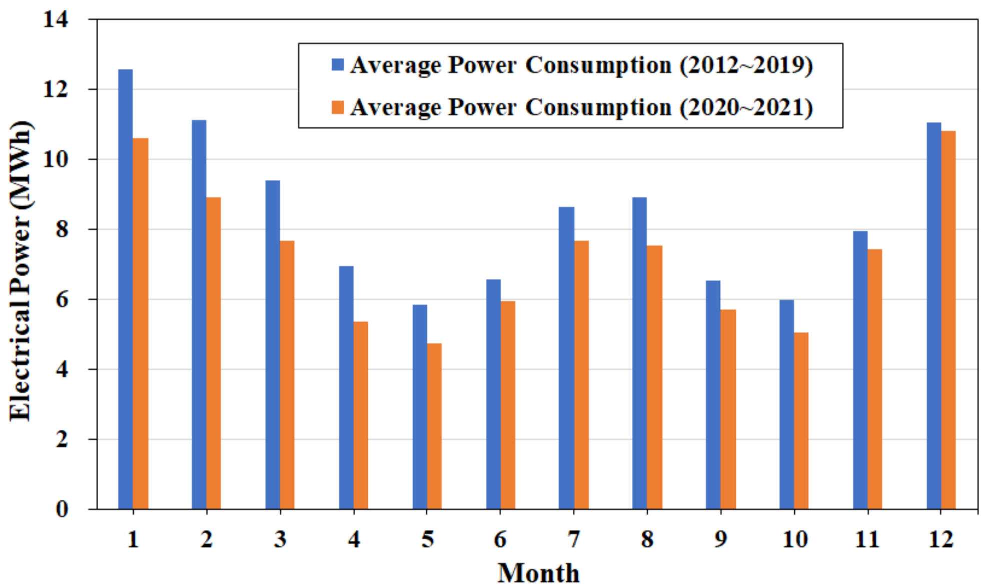


Figure 5. Monthly cumulative power consumptions during 2012–2019 (blue bar graph) and 2020–2021 (orange bar graph).

In order to investigate the effects of heating degree days (HDD) and cooling degree days (CDD) on the heating and cooling energy consumptions, respectively, the HDD and CDD were determined by the following equations [27]:

$$\text{HDD} = \sum (T_r - T_m) \; \forall \; T_r > T_m \tag{1}$$

$$\text{CDD} = \sum (T_m - T_r) \; \forall \; T_m > T_r \tag{2}$$

where T_r is the reference temperature and the T_m is the mean daily temperature. The reference temperatures for the HDD and CDD were taken as 18 °C and 24 °C, respectively, as defined by the Korea Meteorological Administration.

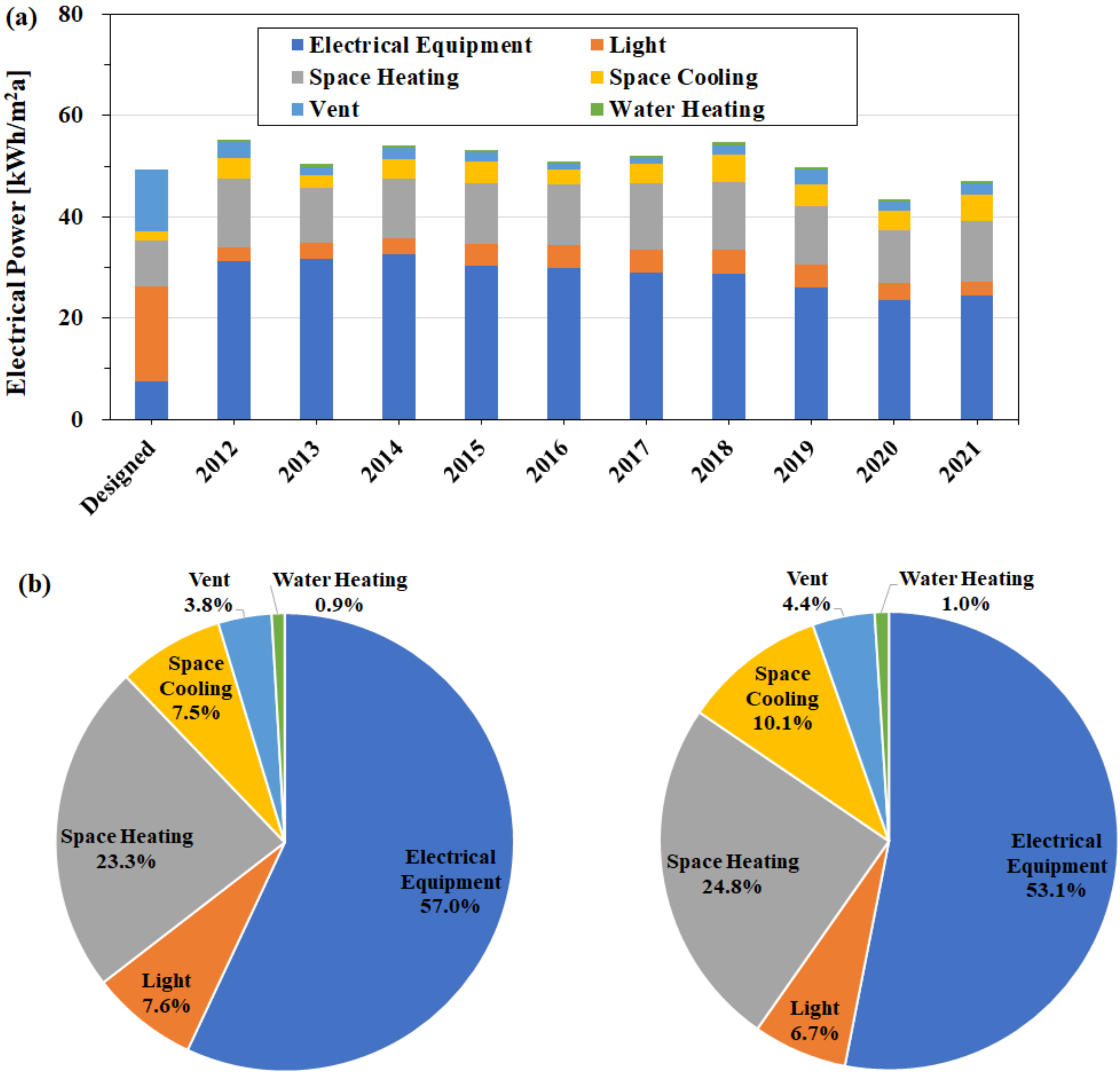


Figure 6. (**a**) Power consumption by end use during 2012–2021; (**b**) comparison on the proportions of power consumption by end use between different periods (2012–2019 and 2020–2021).

Figure 7a shows the HDD and annual energy consumption for space heating, and Figure 7b shows the CDD and annual energy consumption for space cooling. The HDD values ranged from 2469 to 2944 HDD, which are greater than the CDD caused by the weather characteristics in South Korea. The results show that the changes in the electrical power consumed for space heating were significantly affected by the HDD. As shown in Figure 7b, the CDD values ranged from 19 to 221 CDD, and the relation between the CDD and the energy consumption for space cooling was not clear. This was attributed to the shorter space cooling period and the smaller difference between outdoor and indoor temperatures in summer when compared to those of the space heating period. In addition to the CDD effects, the cooling energy consumptions could be affected by the nZEB operation conditions such as the number of occupants, the actual working hours, the usage of electrical equipment, and so on.

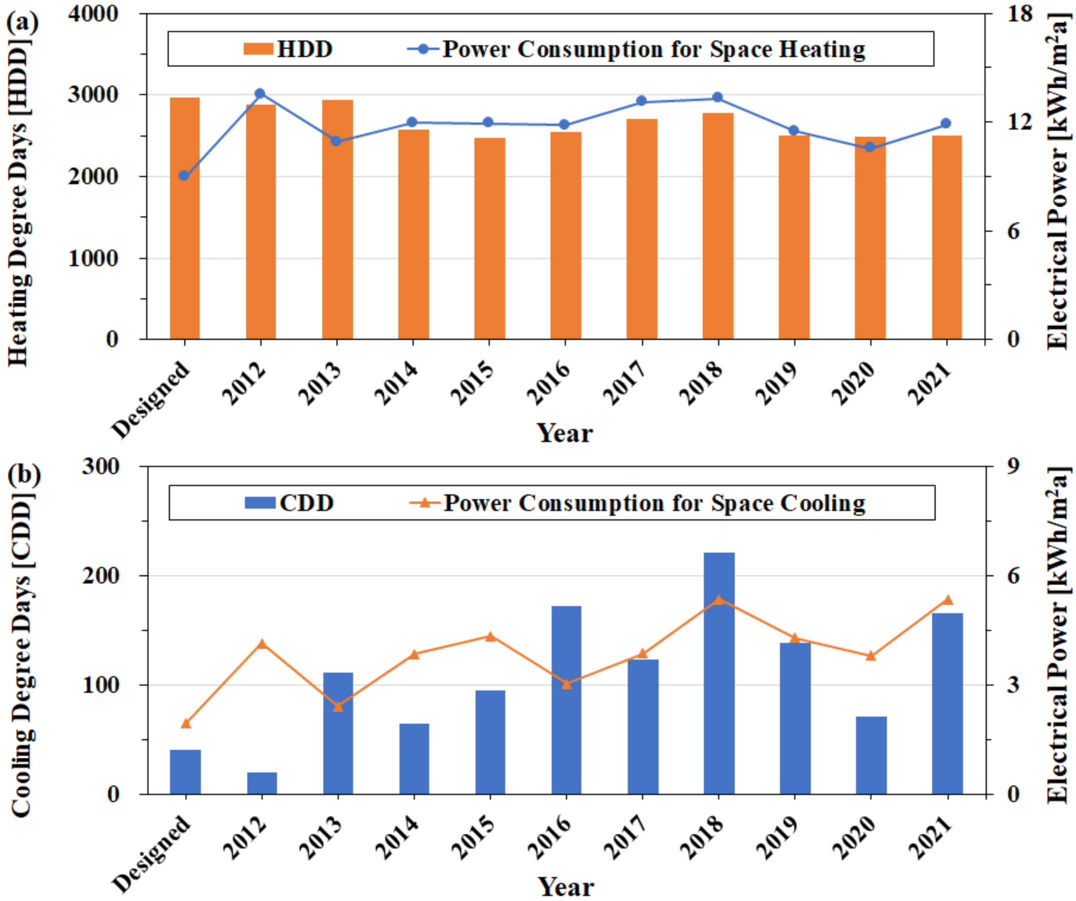


Figure 7. (**a**) Heating degree days and power consumption for space heating; (**b**) cooling degree days and power consumption for space cooling.

3.2. Power Generation Characteristics

The GER building, which is an all-electric edifice, is equipped with PV modules with a generation capacity of 116.24 kWp. Based on the power generation analysis for 2012–2021, Figure 8 illustrates the annual cumulative power generation during this period. Over a decade, the annual average power generation fluctuated between 78.5 MWh and 115.4 MWh, with the average annual cumulative output being 99.0 MWh. The annual power generation ranged from 100.1 MWh to 115.4 MWh during 2012–2018 and from 78.5 MWh to 89.3 MWh in the period 2019–2021. Thus, the average power generation before 2019 was 105.8 MWh, 10.6% higher than the predicted value (95.6 MWh). However, from 2019 to 2021, the average annual power generation dropped to 83.1 MWh, indicating a 21.5% decrease compared to that in the period from 2012–2018, with the value being 13.1% less than that estimated during the design stage. This reduction, possibly due to issues in the PV system (including modules and inverters) post 2019, highlights the need for continuous system monitoring and maintenance for effectively operating the power generation system.

To analyze the monthly power generation characteristics, Figure 9 shows the average monthly cumulative power generated by the PV system. Over the course of 10 years, the average monthly power generation was 8.3 MWh. Based on 2019 as the reference year, when a decrease in the annual power generation was noted, the average monthly power generation was 8.8 MWh for 2012–2018 and 6.9 MWh for 2019–2021. According to the data from the normal operation period of 2012–2018, the power generation in summer and winter was lower than that in spring and fall. The power generated using PV systems is high in spring and fall, due to the clear weather and abundant solar radiation in South Korea, compared to that in winter, owing to less solar radiation, and summer, due to cloudy and rainy days. Although the monthly power generation generally decreased during 2019–2021 due to the seasonal failures in the PV systems, the monthly power generation characteristics portrayed a similar trend to that observed during the normal operation period.

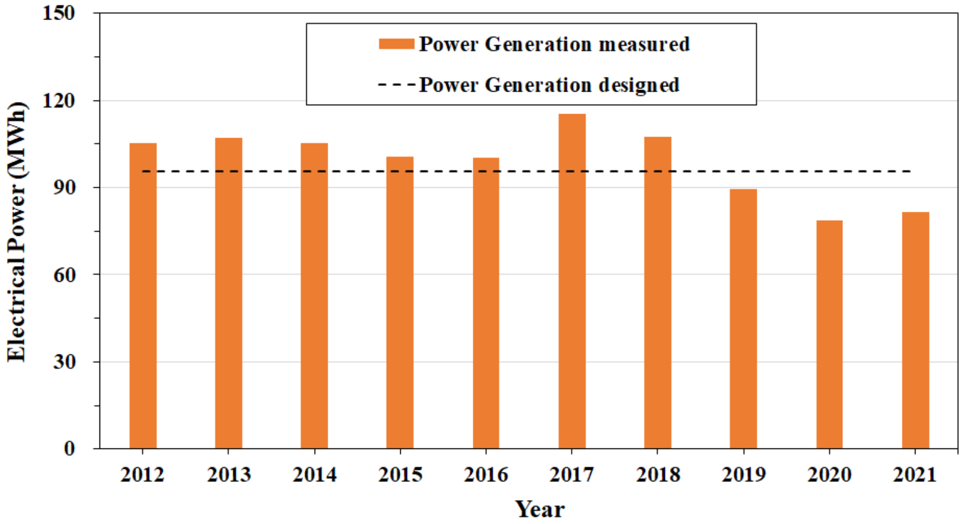


Figure 8. Annual cumulative power generation for 2012–2021.

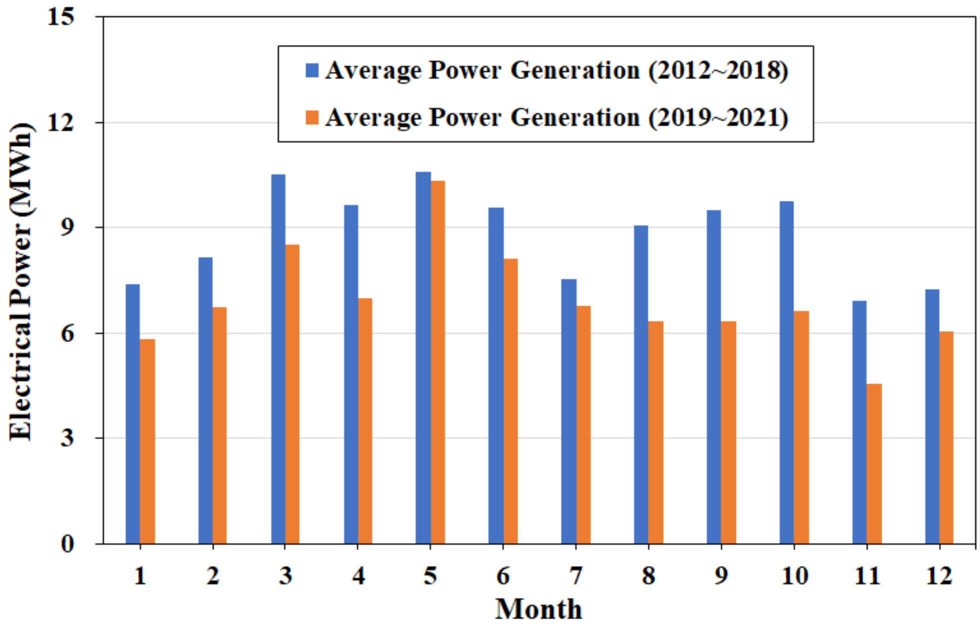


Figure 9. Monthly cumulative power generation during 2012–2018 (blue bar graph) and 2019–2021 (orange bar graph).

As shown in Figure 8, the GER building portrayed a tendency of a significant decrease in power generation from 2019 onwards due to abnormal operation of the PV system. To find the cause of this reduction, Figure 10 shows the monthly power generation from all of the 15 inverters. As a result of investigating the installed PV system, it was found that 20.4% of the installed PV modules and seven inverters (46.7%) malfunctioned over the course of 10 years. Thin-film PV modules were found to have low building applicability due to crack damage from the outset of the PV system operation, and crystalline PV modules also began to fail after about 6 years, with the failure accelerating significantly after 9 years. Specifically, from the beginning of 2012, thin-film PV (amorphous) modules connected to inverters INV-9, INV-10, and INV-11 developed cracks in the glass due to product defects and installation stress, causing thin-film damage from moisture infiltration. After repair and replacement, operation was normalized, except for modules connected to INV-10. However, from 2016, the same problem occurred in the PV modules of INV-11, which stopped its operation in 2017. In the case of crystalline PV modules, the glass-to-glass (GTG) vertical PV modules connected to INV-1 generated less power (by 65%) in April 2021 and stopped operating in November 2021 due to inverter failure. The GTG vertical PV modules connected to INV-3 generated 59.2% less power from December 2020 and stopped operating in October 2021 due to inverter failure. The GTGs vertical PV modules connected to INV-4 operated with 60.6% less power generation from July 2019 and stopped operating in September 2021 due to inverter failure. The GTG vertical PV modules installed in INV-5 generated 65.6% less power after June 2018 due to module defects. The GTG horizontal PV modules connected to INV-6 generated 70.0% less power from December 2017 and stopped operating in November 2021 due to inverter failure. The Glass-to-Tedlar (G–T)/crystal 30-degree tilted PV modules connected to INV-7 generated 72.2% less power from July 2020, while those connected to INV-12 stopped operating in December 2020 due to inverter failure. The GTG vertical PV modules connected to INV-14 stopped generating power in July 2019 due to inverter failure and resumed operating in November 2020 after the inverter was repaired. Additionally, as shown in Figure 9, from January 2018 to March 2018, real-time power generation data were not recorded due to the communication problem with inverters. By analyzing the total power generation data, it was found that the PV system operated properly. Thus, these incidents highlight the importance of continuous maintenance through data monitoring and analysis to enhance the effectiveness of nZEBs. Furthermore, proper maintenance budgeting based on the analysis of maintenance status and prompt failure diagnosis and response are crucial for the effective management of nZEBs. Figure 11 portrays the major faults in the PV system operation that occurred during the 10-year study period, e.g., module cracks, dust deposits, performance degradation, and inverter failure [28,29].

3.3. Energy Balance Analysis

The energy performance analysis of an nZEB is typically conducted through energy balance analysis by comparing the total annual energy production and consumption to determine the adherence to net-zero energy. The GER building, which was an all-electric nZEB, uses a PV system to ensure net-zero energy. However, PV systems generally can lead to the instability of the power system due to real-time mismatch between power generation and consumption. Accurate diagnoses of such disparities require real-time analyses that are based on actual power generation and consumption data. Therefore, this study analyzed the annual, monthly, daily, and hourly power consumption and generation characteristics using the 10-year power consumption and generation data of the GER building. Figure 12 shows the differences between the annual cumulative power generation and consumption for 2012–2021. During the seven years before 2019, when the PV system output decreased significantly, the building achieved a net-zero energy status, with surplus energy, The only exception was noted in 2012 and 2015; in these two years, power generation was less than the power consumption of the building by only 1.0% and 2.1%, respectively, indicating a "near nZEB" status. During the period between 2019 and 2021, when the power generation decreased considerably due to the failure of the PV system, the power generated fell short of the power consumed by 7.8% on average. From 2020, despite the reduction in the annual cumulative power consumption due to COVID-19, net-zero energy could not be achieved due to the decrease in power generation caused by the PV system failure. This highlights the importance of continuously monitoring the operation status of nZEBs and ensuring normal operation through the maintenance of facilities to achieve net-zero energy.

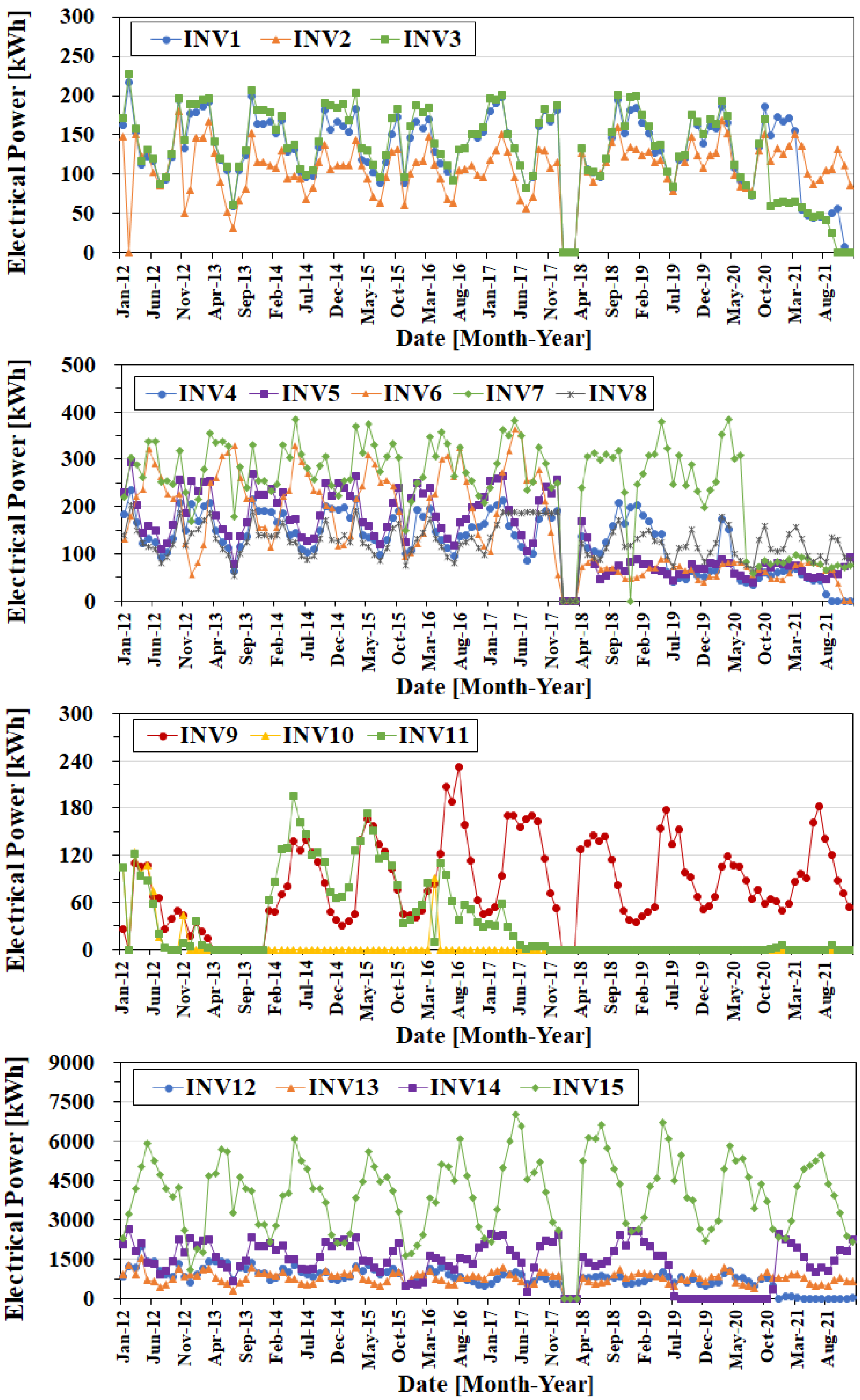


Figure 10. Monthly cumulative power generations of all of the inverters (INV1–INV15).

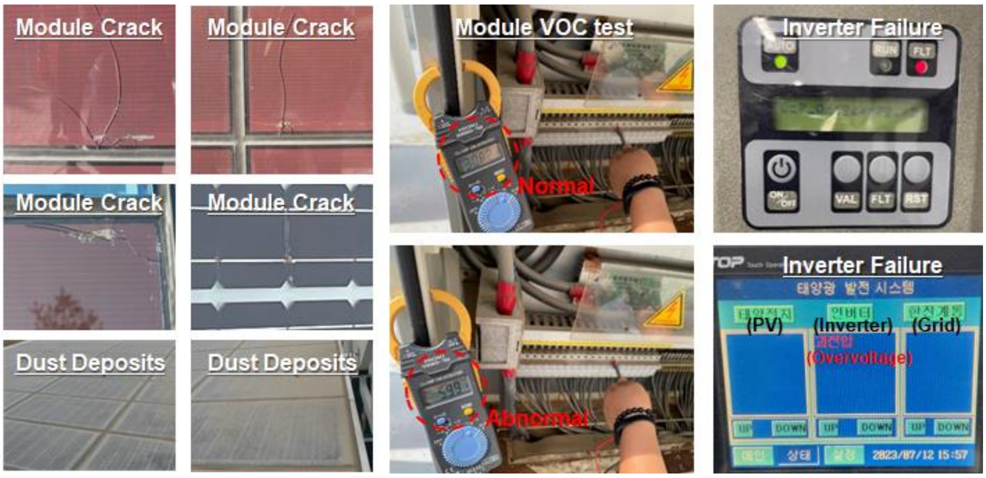


Figure 11. Major faults for photovoltaic (PV) system.

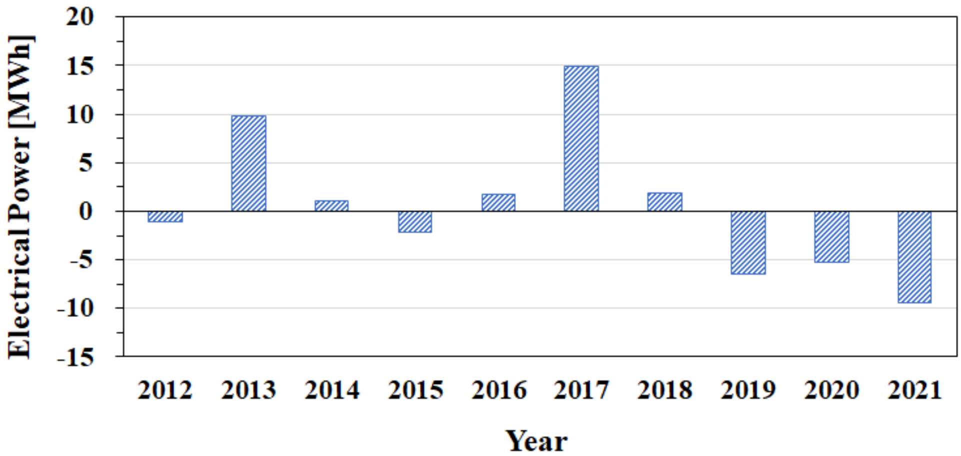


Figure 12. Differences in the power generation and consumption for 2012–2021 based on annual cumulative data.

To compare the characteristics of the surplus and shortage of power generation, this study analyzed the data at yearly, monthly, daily, and hourly intervals. The real-time data for the years 2012, 2013, 2014, 2016, and 2019 were used because there were no real-time missing data. The annual cumulative surplus and shortage of power for the years 2012, 2013, 2014, 2016, and 2019 are illustrated in Figure 13a,b, respectively. Except for the analysis of the annual data, all other analyses based on data at the monthly, daily, and hourly intervals confirmed the occurrence of both surplus and shortage of power every year. Although surplus power did not occur in the 2012 and 2019 annual cumulative data analysis, surplus and shortage power was observed in the monthly, daily, and hourly data analysis. The surplus and shortage amount increased as the analysis time interval decreased. An hourly data-based analysis revealed a power surplus of 56.4 MWh and a shortage of 54.3 MWh on a yearly basis. Other buildings within the NIER research complex consumed the surplus energy produced from the GER building. However, due to significant power loss in transmission and transformation, it is necessary to apply energy storage or conversion facilities to minimize the surplus power and maximize the power usage within the GER building. Additionally, enhancing the energy self-consumption rate can resolve the instability in the power grid caused by the mismatch between power generation and consumption, contributing to the accelerated dissemination of nZEBs.

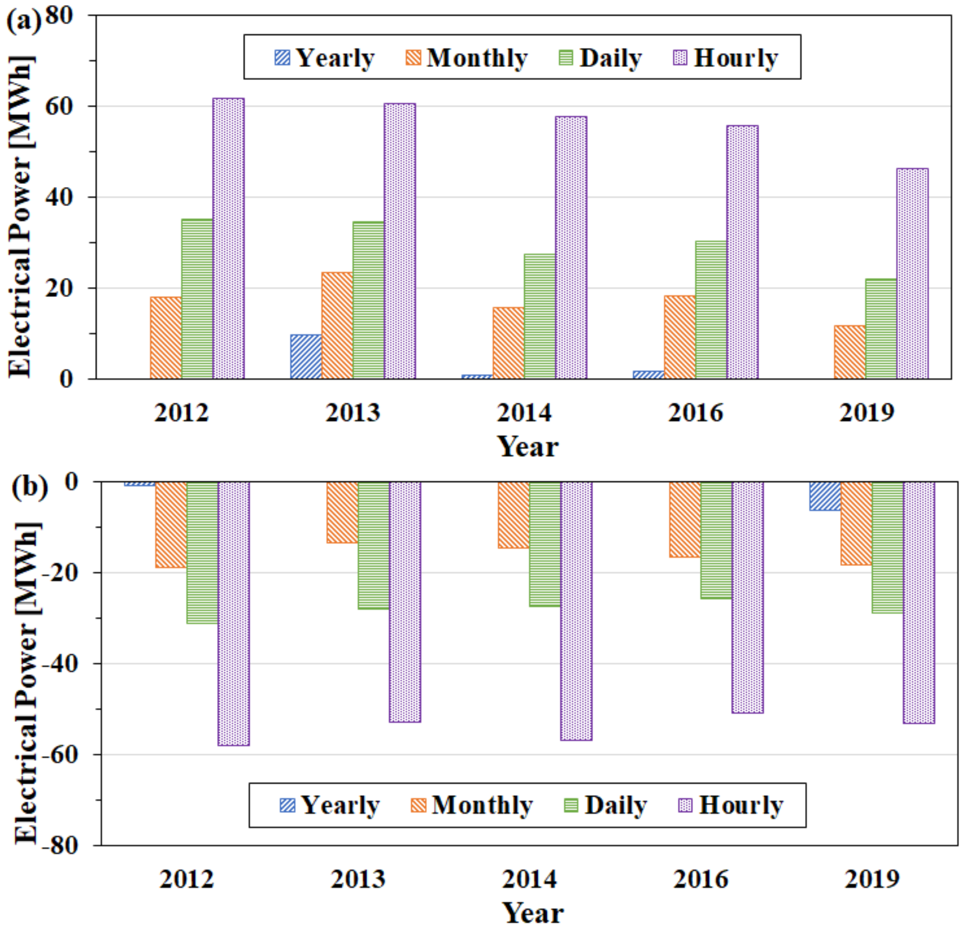


Figure 13. Comparison of (**a**) surplus power and (**b**) shortage power data for different intervals.

To examine the characteristics of the monthly cumulative surplus and shortage of power in the GER building, hourly power consumption and generation data were analyzed. Figure 14 depicts the monthly cumulative surplus and shortage for the years 2012, 2013, 2014, 2016, and 2019 based on real-time power generation and consumption data (hourly data). The experimental results show that the average monthly surplus power was 4.7 MWh. The average monthly surplus power in summer (July–August) and winter (November–February), known to have high heating and cooling loads, was 3.4 MWh. In contrast, an average monthly surplus power of 6.1 MWh in spring (March–June) and fall (September–October) was noted due to the minimal heating and cooling loads, which was 1.79 times greater than that observed in the high heating and cooling load seasons. Due to the mismatch in power generation and consumption, an average monthly power shortage of 4.5 MWh was noted. The results also showed an average monthly power shortage of 3.3 MWh in the low power consumption seasons (spring and fall) and 5.8 MWh in the high power consumption seasons (summer and winter). This exhibited a trend contrary to that of surplus power, with the power shortage being 1.76 times higher in summer and winter compared to that in spring and fall. During spring and fall, the cumulative surplus power exceeded the cumulative shortage power, invariably resulting in surplus power, even with an increase in self-consumption. Conversely, the shortage of power was higher than the surplus power in summer and winter. In this context, a thorough technical and economic analysis is vital for the efficient application of energy storage and conversion technologies to enhance the self-consumption rates and mitigate the power system instability. Furthermore, it is essential to explore novel strategies that can minimize transmission and distribution losses by developing a zero-energy community within the NIER research complex that is in tandem with buildings that exhibit diverse load patterns.

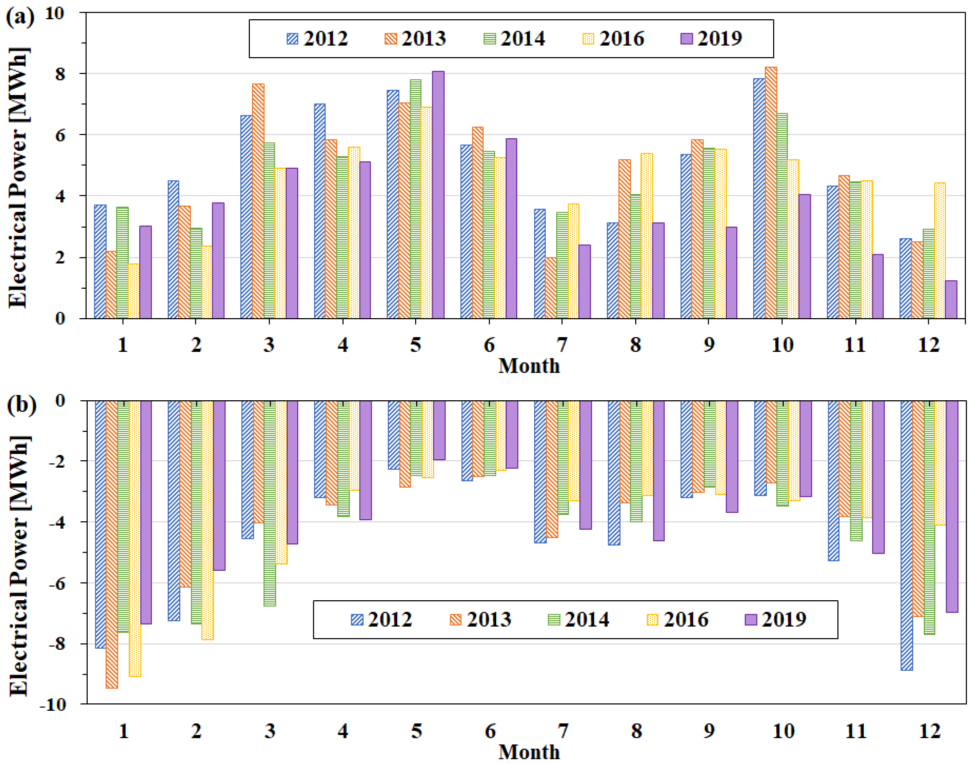


Figure 14. Differences in monthly cumulative (**a**) surplus power and (**b**) shortage power based on hourly data.

Based on the real-time power consumption and generation data, the load coverage factor (LCF) and supply coverage factor (SCF) were used as the indicators to evaluate the load matching rate between the generated energy and energy demand [24,30,31]. The LCF represents a ratio of energy demand covered by the power generation and total energy demand and is defined by the following equation:

$$\text{LCF} = \frac{\int_{\tau_1}^{\tau_2} min[g(t),\, l(t)]dt}{\int_{\tau_1}^{\tau_2} l(t)dt} \tag{3}$$

where $g(t)$ is the generated energy and $l(t)$ is the energy load.

The SCF represents a ratio of the generated energy consumed for the energy demand and the total energy generated and is determined by the following equation.

$$\text{SCF} = \frac{\int_{\tau_1}^{\tau_2} min[g(t),\, l(t)]dt}{\int_{\tau_1}^{\tau_2} g(t)dt} \tag{4}$$

Figure 15 shows the annual values of LCF and SCF for the years 2012, 2013, 2014, 2016, and 2019 based on hourly measured data. The annual values for the LCF and SCF ranged from 0.35 to 0.37 and from 0.30 to 0.35, respectively. The low LCF and SCF values could be caused by both the mismatch between energy production and demand and the lack of use of the energy storage system in the GER building. Figure 16 shows the monthly average values of the LCF and SCF for the years 2012, 2013, 2014, 2016, and 2019. The monthly average LCF was the lowest in winter, peaking in December at approximately 0.23 because of both the increase in the energy consumption for heating and the decrease in the PV power generation. The LCF was the highest in spring, peaking in June at approximately 0.48 due to both the low energy demand and the sufficient energy production. The highest SCF was 0.43 in July (in summer) owing to a substantial portion of the generated PV power being used for cooling. The lowest SCF was 0.25 in October (in fall) owing to the high energy generation and the low energy demand. Since the PV power generation is strongly affected by the outdoor environment, there is a mismatch between energy production and consumption, resulting in the reduction in the load matching rate. Thus, energy storage and conversion technologies should be applied to enhance the energy performance of nZEBs.

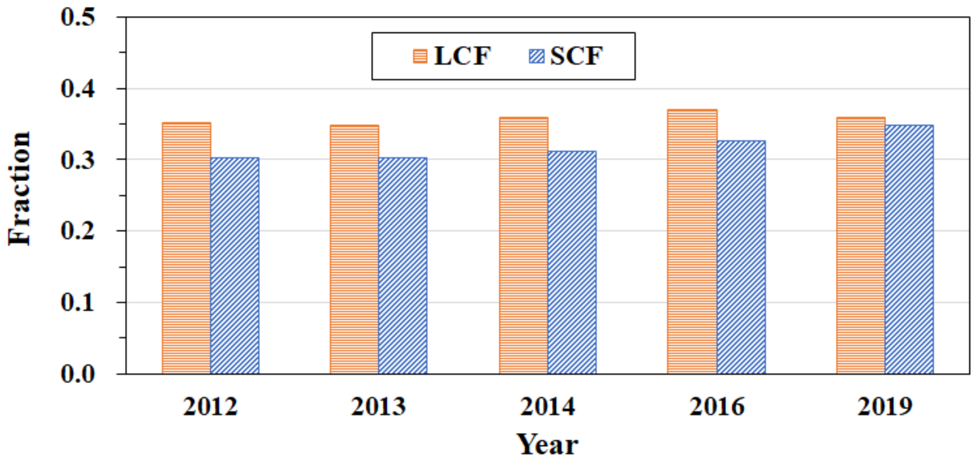


Figure 15. Annual LCF and SCF for the years 2012, 2013, 2014, 2016, and 2019.

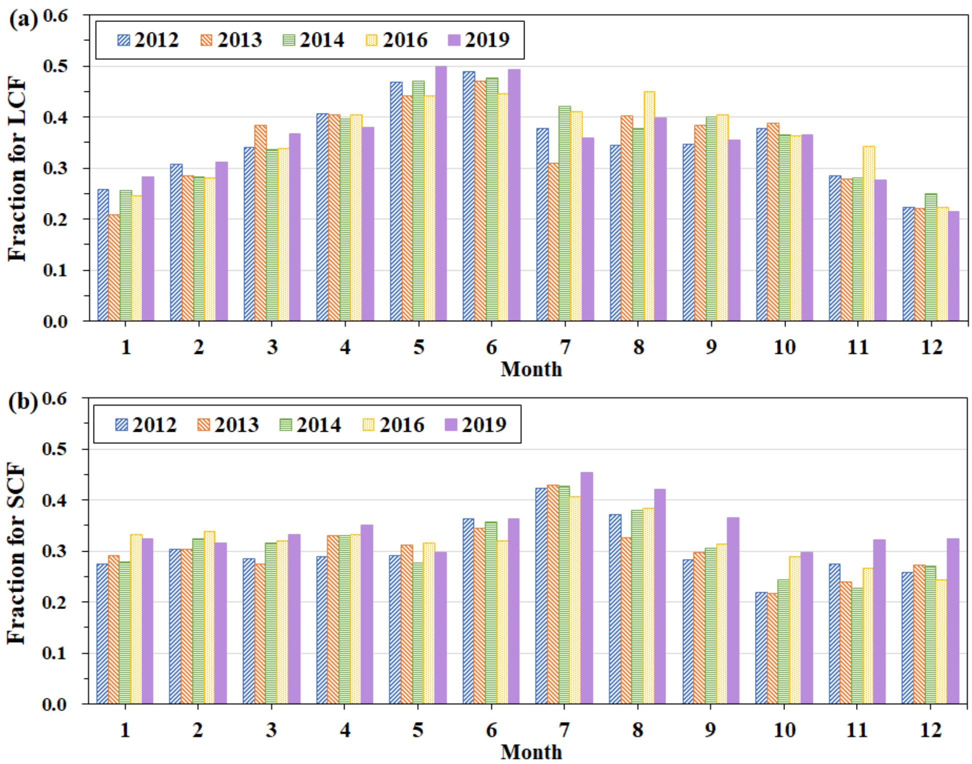


Figure 16. Monthly LCF (**a**) and SCF (**b**) for the years 2012, 2013, 2014, 2016, and 2019.

To analyze the detailed characteristics of the power surplus and shortage in each season, the power consumption and generation data for 2014 were used because they were close to the average annual power consumption and generation during normal operation. May, July, October, and January were chosen as the representative months for each season. Figure 17 depicts the variations in the real-time power consumption and generation in these months. In May (spring) and October (fall), except for days with low solar power generation due to cloudy skies, there was a surplus power during PV system operation and a power shortage during non-solar hours in the day. In January (winter) and July (summer), when most of the power produced during the day was used for heating and cooling, the surplus power was lower compared to that in May and October, with power shortages still observed during non-solar hours. As the GER building was an office building, only the base load power was consumed on weekends, indicating a higher surplus energy generation during the day on weekends compared to that on weekdays, with the only exceptions being noted on low solar radiation days.

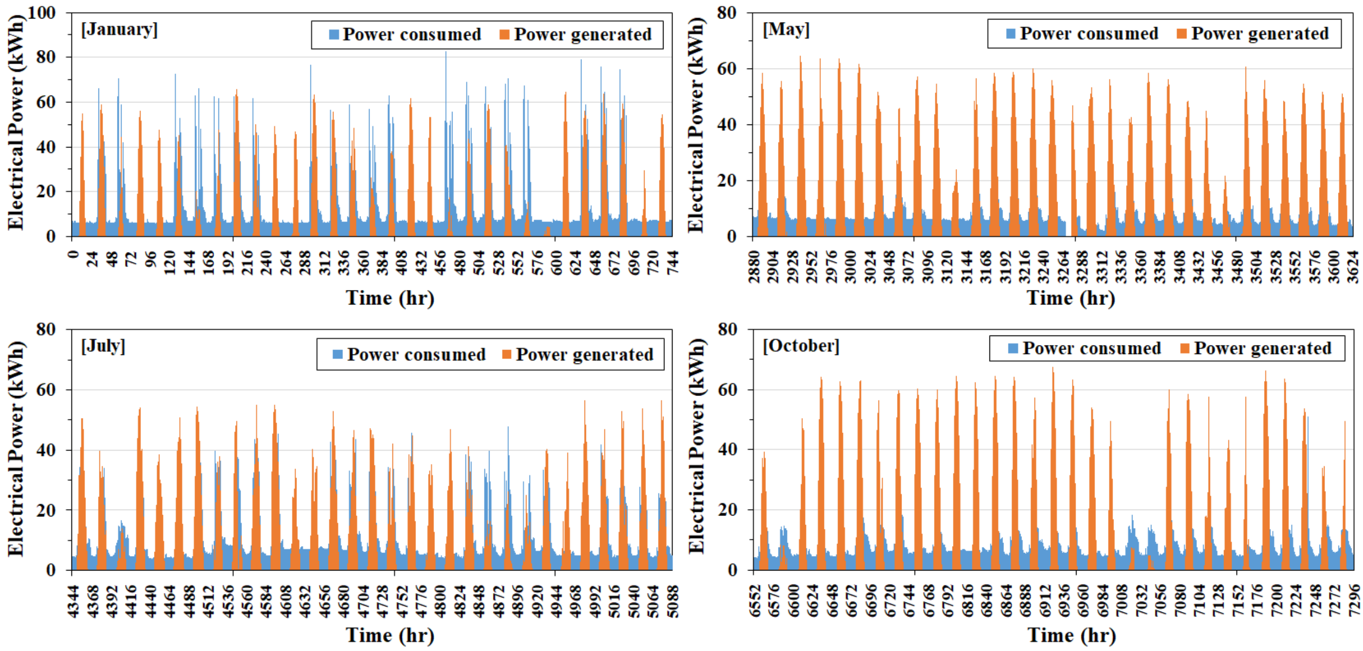


Figure 17. Variations in the real-time power generation and consumption in representative months.

A detailed examination of power production and consumption based on the time of day was conducted. Figure 18 illustrates the variations in the real-time power consumption and generation over a week in each representative month based on the data shown in Figure 17. The weekday data for January and July indicated that the onset of power consumption for heating and cooling, which occurred before PV power generation began, led to a significant power shortage around the morning commuting hours. During high noon, when PV modules were at peak production, high surplus power was generated as well. During other times of the day, the surplus and shortage of power were intermittently generated, depending on the energy consumption for heating and cooling and the solar power generation. A continuous power shortage occurred in the absence of solar radiation. Over the weekends, part of the generated power was consumed by the building's base load, with the remainder being the surplus. The surplus quantity generated during the weekends was greater than that generated on weekdays. In normal power generation conditions, the weekday data for May and October revealed a continuous generation of surplus power during daylight hours, with intermittent power shortages being evident in the absence of solar radiation. The surplus and shortage power generation characteristics during weekends in May and October are similar to those in January and July, but the difference in the surplus power generated on weekdays and weekends was smaller in May and October than that in January and July. In light of these findings, the variations in the power surplus or shortage within the building, which depended on the daily, weekly, monthly, and seasonal building operation and external environmental changes, emphasized the need for a comprehensive strategy. Notably, effective energy operation of nZEBs, while considering the utilization of energy storage, conversion, and sharing technologies, is essential for addressing such fluctuations.

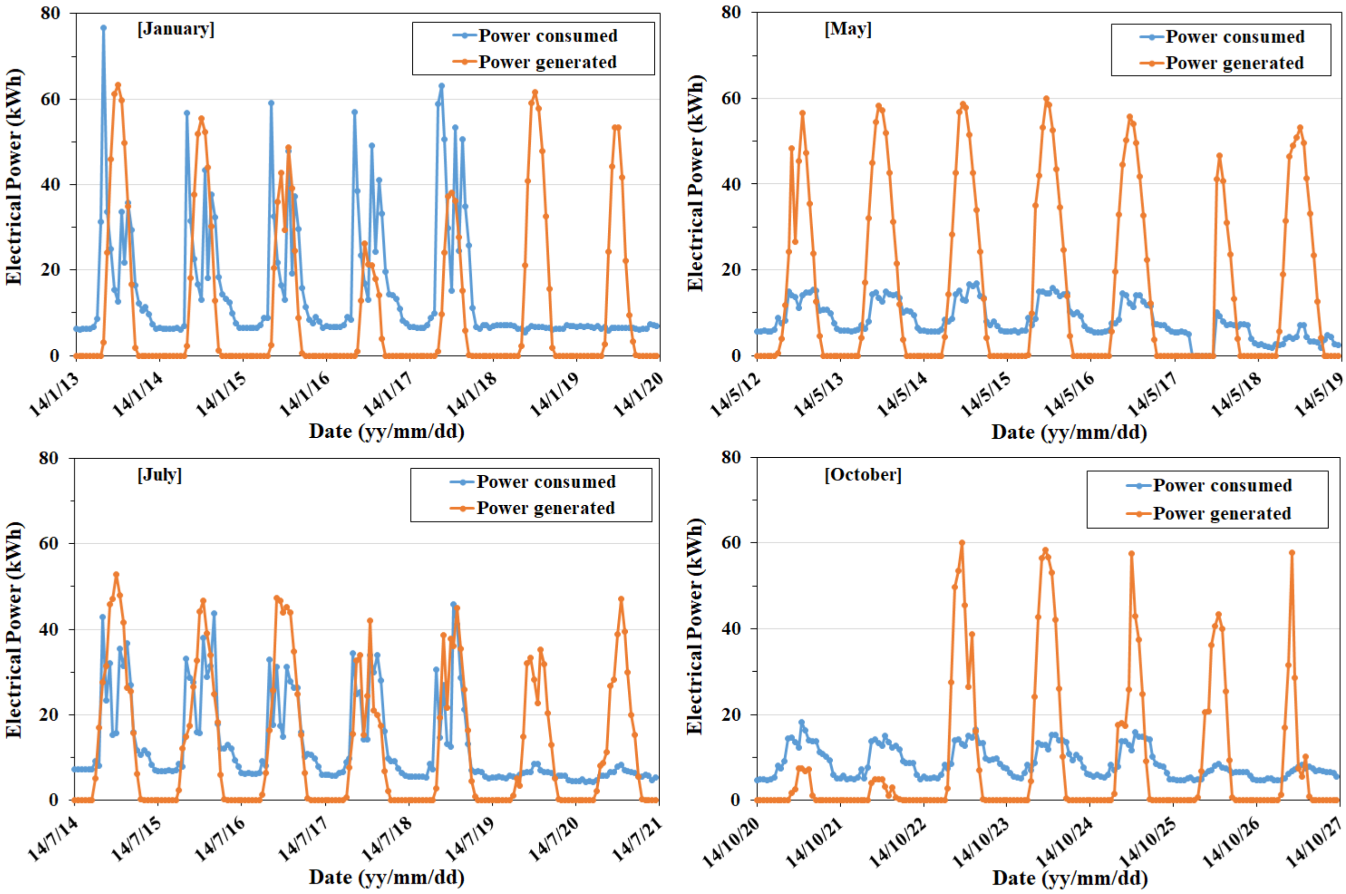


Figure 18. Variations in the real-time power generation and consumption for a week in representative months.

4. Conclusions

In this study, the energy consumption and generation characteristics, the operation status of the PV power generation system, and the energy balance of the GER building, which is an nZEB, were analyzed based on the long-term data for 2012–2021 to assess its practical effectiveness. The main findings of this study are summarized below.

- The average annual cumulative power consumption of the nZEB was 101.3 MWh, 6.2% higher than the power consumption estimated at the design stage. During the COVID-19 pandemic, the annual average power consumption decreased by 13.9% (to 87.3 MWh) due to the reduction in the workforce.
- The PV system of the nZEB had an annual power generation capacity of 105.8 MWh, indicating an increase of 10.6% compared to the power generation estimated during the design stage. Due to the failure of PV systems such as module cracks, inverter failures, and performance degradation, the average annual power generation from 2019 to 2021 was 83.1 MWh, indicating a decrease of 21.5% compared to that generated from 2012 to 2018.
- From the perspective of an energy balance analysis, the nZEB achieved a net-zero energy status for 5 out of the 7 years of normal operation (2012–2018) by fulfilling a surplus energy balance. However, it was found that every year, there were both a surplus and shortage of power from the data analysis with the reduced time intervals. The hourly data analysis results indicated an average annual energy surplus of 56.4 MWh, while the energy shortage was noted at 54.3 MWh. In addition, the load matching analysis showed that the annual LCF and SCF were approximately 0.36 and 0.32, respectively.

- From the long-term operation data, it was found that the advanced nZEB design, hourly data-based energy analysis, fault diagnosis and maintenance, and the strategies enhancing the self-consumption rate should be considered to expand nZEB dissemination.

In future studies, the energy production and consumption analysis for nZEBs will be continuously conducted to evaluate the energy performance, and fault diagnosis and maintenance technology will be developed using the actual operational data. In addition, the optimization analysis for the energy balance will be carried out to achieve the goal of zero energy consumption. Furthermore, a demonstration study for nZEBs with energy storage and conversion technologies will be conducted to enhance the self-consumption rates and to expand nZEB dissemination.

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