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# Analysis on Operation Modes of Residential BESS with Balcony-PV for Apartment Houses in Korea

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**Abstract:** The integration of battery energy storage systems (BESS) with renewable energy is a potential solution to address the disadvantages of renewable energy systems, which is irregular and intermittent power. In particular, residential BESS is advancing in numerous countries. The residential BESS connected to the photovoltaic system (PV) can store the PV power in the battery through charging, and supply the PV power, which was stored in the battery, to the load through discharging when there is no PV power. Therefore, the utilization of residential BESS with PV reduces the daily electric power consumption and the electricity bills that households have to charge. However, it is understood that there is no case of installing and using residential BESS in Korea yet. Most residential houses in Korea are apartment houses, and thus residential BESS can be used with balcony PV. This paper presents operation modes of residential BESS with balcony PV for apartment houses. The BESS capacity was estimated by considering the balcony PV capacity, which can be installed in households, and power consumption. The applicability of the residential BESS was analyzed through performance and economics evaluation under current and various conditions. The operation modes of BESS were divided into four types according to PV power supply priority and battery charging source, and a test took place in a demonstration house. The risk of fully discharging the battery has been discovered when PV power is first charged to the battery or when only PV power is charged with the battery. As a result, preferential charging of the battery with PV power and then with PV and grid power was found to be the most optimal operation mode. In addition, additional functions were proposed for residential BESS in apartment households. The results will contribute to effective application of residential BESS with balcony PV in the near future.

**Keywords:** BESS (battery energy storage system); balcony photovoltaic system; apartment houses; operation modes; zero-energy houses

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## 1. Introduction

With increasing interest in zero-energy buildings, which minimize energy consumption in buildings, a battery energy storage system (BESS) along with a renewable energy system is also attracting attention for their efficient energy management [1,2]. Among renewable energy systems, photovoltaic systems (PVs) are most commonly installed in buildings to reduce energy consumption. However, PVs have a disadvantage in that they supply power only during solar radiation time. By connecting BESS, PV power can be stored and supplied at other times [3,4]. In particular, the market for residential BESS is expanding internationally in regards to zero-energy houses. The operation of the residential BESS with PV can show the effect of reducing the daily electric power consumption and the electricity bills. In addition, it can increase the rate of self-sufficiency electric power in the household.

North America, Europe, and Japan are encouraging dissemination by offering a variety of benefits, such as subsidies and tax reductions for the residential BESS. However, it was investigated that there is no market for residential BESS in Korea yet because of the high price of residential BESS, low electric rate, progressive rate system, and limited PV capacity [5]. The residential BESS used overseas is for detached houses and has a capacity of 3–10 kWh, so at least 1–3 kW of PV capacity is required. In contrast, most residential houses in Korea are apartment houses. Individual households of apartment houses use a small capacity balcony PV of around 1 kW, and not a rooftop PV. Further, the surplus PV power remaining after it has been supplied to the load cannot be sold in households. Therefore, BESS implemented overseas cannot be readily used in Korea.

Research topics for using the residential BESS with PV are typically operation scheduling, capacity calculation, economic analysis, etc. Research related to this was conducted under variable electric power rate conditions such as Time-of-Use (TOU) pricing and Real-time Price (RTP), which are demand-managed options. Yoon et al. performed simulations for the control of a residential BESS using energy generation and consumption data for 64 residences with the Pecan Street Project in the United States and a range of seasonal dynamic price tables [6]. Hassan et al. developed a model to optimize FiT (PV generation and export tariff) revenue streams of PVs with BESS and simulated it as residential data [7]. Vieira et al. modeled and simulated BESS with PV with real data and MATLAB/Simulink for residential buildings in Portugal, showing a reduction on the energy sent and consumed from the grid, as well as the energy bill [8]. Jung et al. developed an optimal scheduling model of BESS with PV in residential buildings using the electric power and electricity price variables in Korea through simulation using a Python and Cplex solver [9]. Ratnam et al. organized the optimization approach methods for the scheduling of BESS with residential PVs to assess the customer benefit under incentives, such as time-of-use (TOU) pricing, feed-in-tariffs, and net metering [10]. Cucchiella et al. proposed the economic feasibility of residential lead-acid BESS combined with PV panels in Italy and the assumptions at which these systems become economically viable combined of electric power prices, investment costs, tax deduction and etc. [11]. Stelt et al. assessed and compared the technical and economic feasibility of both Household Energy Storage (HES) and Community Energy Storage (CES) in Netherlands using a mathematically optimized Home Energy Management System (HEMS) schedules scenario [12]. Koskela et al. analyzed the profitability and sizing of a photovoltaic system with an associated BESS from an economic perspective for an apartment building and detached houses in Finland [13]. Mulleriyawage et al. tried to calculate the optimal capacity for the fiscal benefits based on the TOU (Time-of-Use) tariff scheme because it is difficult to use residential BESS due to its expensive price in Australia [14]. These studies were based on the entire building, not the unit of apartment households.

This paper presents operation modes of residential BESS with balcony PV for individual households of apartment houses in Korea. An experiment on various operation modes was conducted in a demonstration house. The results of this experiment show that some functions need to be added for residential BESS to be made applicable to individual households of apartment houses in Korea.

## 2. Experiment Method

### *2.1. System Configuration*

BESS connected with a PV consists of a battery pack, Power Conversion System (PCS; included DC/DC converter and AC/DC Inverter), Battery Management System (BMS), and Power Management System (PMS). The BMS is installed inside the battery pack to protect and control the battery, and the PMS manages the PCS and the BMS. The residential BESS installed in a residential building are typically connected to the PV module, with the load and grid as shown in Figure 1 [15]. In particular, as this load is a battery load separate from the grid, the battery discharge power is supplied only to the home appliance connected to the load line. The load is supplied with the PV or battery power, and the remaining PV power can be stored in the battery and supplied at the required time.

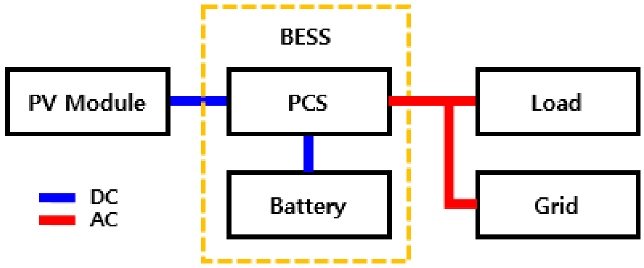


**Figure 1.** Schematic diagram of battery energy storage system (BESS) with photovoltaic system (PV).

As mentioned earlier, Korea has many apartment houses and the PV capacity that can be installed in individual households is limited. The capacity of the balcony PV is about 300 W (PV module 1ea) per household and it can be larger by connecting the PV modules in series [16]. Therefore, BESS should be designed and operated in consideration of the environment used. The operation mode of the residential BESS can basically charge the battery with PV power and the PV power can be set preferentially to either load or battery. The battery is charged with grid power when the battery is in system check or the SOC (state of charge) level of the battery is at an emergency level.

### 2.2. Experiment Apparatus and Method

In order to analyze the operation modes of the residential BESS connected with the balcony PV, an experiment was conducted in one household of a demonstration house in Goyang City. The experimental apparatus included a 2.016 kWh BESS prototype (48 V 42 AH LiFePO4 Battery, 1 kW PCS, All-in-one type, efficiency 93%), a 1.2 kW balcony PV (300 W module 4 series connection, efficiency 18%, south facing, installation tilt angle 70°), and an electric fan (power consumption 260 W). The BESS capacity was estimated by considering the capacity of the balcony PV, which can be installed in individual households, and the total household power consumption. For data collection, a PCS monitoring software (SolarPower) was used for the PV, battery, and load side. On the grid side, data were collected using a power meter (Wattman Power Meter) and a power monitoring software (Wattman Viewer). The inclined solar radiation and temperature were measured using a pyranometer (EKO MS-602), a thermocouple (TC-T), and a data logger (GRAPHTEC 260-16CH). The items data that were measured are PV generation power (kW), battery voltage (V) and current (A), load power (kW), grid power (kW), solar radiation (W/m$^2$), PV module temperature (°C), and outdoor temperature (°C). The data sampling/recording time was 1 s/1 min (average 60 s). Figure 2 shows the apparatus used in the experiment.

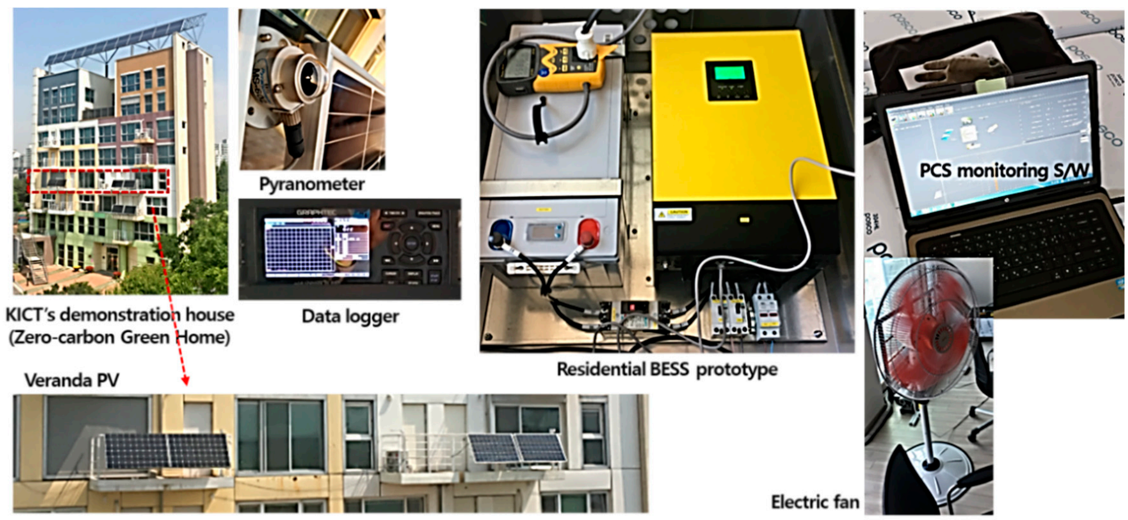


**Figure 2.** Photographs of the building and experiment apparatus.

The basic settings for BESS operation were set to battery bulk charge voltage 58.4 V, battery discharge cut-off voltage 41 V, and battery re-charge voltage 44 V. The experimental procedure was to set four operation modes for 3 days and to connect the electric fan as a load at 13:00 on the first day of changing the operation mode.

According to the PV power supply priority and battery charge source, the operation mode of BESS was divided into four, as shown in Table 1. Mode 1 preferentially supplies PV power to the load and charges the battery only with PV power. Mode 2 supplies PV power to the load first and charges the battery with PV and grid power. In mode 3, the battery is preferentially charged with PV power, and only the PV power is supplied. Mode 4 preferentially charges the battery with PV power and then with PV and grid power. Figure 3 is a schematic diagram of PV power supply priority and battery charge source.

**Table 1.** Operation modes of BESS.

| Operation Mode | PV Power Supply Priority | Battery Charge Source |
|---|---|---|
| Mode 1 | Load | PV only |
| Mode 2 | Load | PV and Grid |
| Mode 3 | Battery | PV only |
| Mode 4 | Battery | PV and Grid |

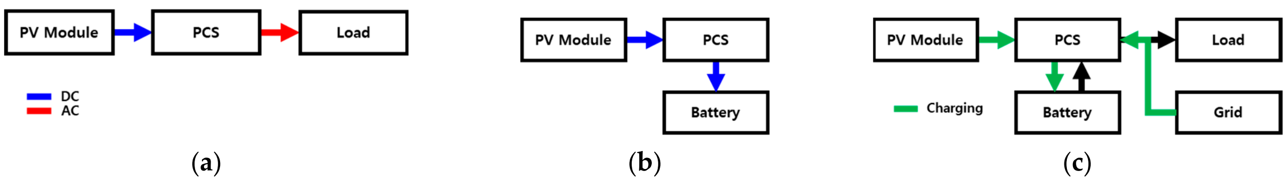


**Figure 3.** Schematic diagram of BESS operation: (**a**) PV power supply to load first; (**b**) PV power supply to battery first; (**c**) battery charge source.

## 3. Experiment Results

The power data per day were analyzed for each operation mode of BESS. The experiment lasted about 3 months from 21 August 2019 to 8 November 2019. In order to check the charging and discharging results, the experiment was conducted on all days except rainy days and days that the apparatus were checked. This paper describes by selecting an experimental date that representatively showed the characteristics of the modes. In this experiment, the connection load was an electric fan with a power consumption of 260 W, but it actually consumed 200 W. For reference, the PV power differed between day to day due to weather effects. Table 2 summarizes the experiment date, weather, load, and BESS states for each mode.

**Table 2.** Experiment schedule, weather, and state by BESS operation mode.

| Mode | Date | Weather | BESS State |
|---|---|---|---|
| Mode 1 | 2019.08.23 (Fri.) | Sunny | Load connection at 13:00 |
| | 2019.08.24 (Sat.) | Cloudy | Full discharge |
| | 2019.08.25 (Sun.) | Sunny | |
| Mode 2 | 2019.08.27 (Tue.) | Rainy | Load connection at 13:00 |
| | 2019.08.28 (Wed.) | Cloudy | - |
| | 2019.08.29 (Thu.) | Rainy | - |
| Mode 3 | 2019.11.05 (Tue.) | Sunny | Load connection at 13:00 |
| | 2019.11.06 (Wed.) | Partly Cloudy | Full discharge |
| | 2019.11.07 (Thu.) | Sunny | |
| Mode 4 | 2019.09.17 (Tue.) | Cloudy | Load connection at 13:00 |
| | 2019.09.18 (Wed.) | Sunny | - |
| | 2019.09.19 (Thu.) | Sunny | - |

Under mode 1, the experiment was conducted for a total of 3 days from 23 to 25 August 2019. The weather was cloudy. Figure 4 shows the graph of time variations of the daily PV, battery, grid and load power, battery voltage, and battery capacity (SOC) in mode 1. For reference, the grid power in the graph was expressed without distinction between supply and demand based on households. Charging started at 06:18 and was completed at 09:54 on 23 August 2019. The power was fully discharged about 10 h after the battery began to discharge. The discharge power was 1.854 kWh (discharge peak power of 0.199 kW), and the load power at this time was 2.037 kWh. An intermittent discharge occurred between 15:00 and 17:00, but the start and end times of discharge were at 17:33 on 23 August 2019 and at 03:36 on 24 August 2019. About 92% of the battery capacity was discharged and about 91% of the load was supplied to the battery. In this mode, the battery voltage reached about 33 V, which is the full discharge voltage range. Therefore, the battery could not be used because the battery voltage could not be maintained until the next PV charge.

Mode 2 was designed to charge with grid power when the battery voltage drops below the reference voltage while PV charge is not possible. The experiment was conducted for a total of 3 days from 27 to 29 August 2019. The weather was rainy and cloudy. Figure 5 shows the graph of time variations of the daily PV, battery, grid and load power, battery voltage, and battery capacity (SOC) in mode 2. The battery began to discharge at 17:41 on 27 August 2019 and ended at 03:38 on 28 August 2019. It remained discharged for about 9 h and 45 min. The total discharge power was 3.733 kWh (discharge peak power of 0.249 kW), and the load power at discharge was 3.875 kWh. Similar to mode 1, intermittent discharge occurred between 16:00 and 17:00, before the discharge start time. On 28 August 2019, the battery voltage fell at 4:00, but the battery voltage was maintained without further dropping due to the charging of the grid power. The battery was charged with 0.365 kWh of grid power. Since PV power is supplied to the load with priority, it is impossible to charge the battery if there is no remaining PV after being supplied to the load. Therefore, it is necessary to prevent the discharge by reducing the battery idle time and charging the grid power.

Under mode 3, the experiment was conducted for a total of 3 days from 5 to 7 November 2019. The weather was sunny and partly cloudy. Figure 6 shows the graph of time variations of the daily PV, battery, grid and load power, battery voltage, and battery capacity (SOC) in mode 3. Charging started at 07:38 on 5 November 2019 and full charge was reached at 11:31 on 5 November 2019. The battery was fully discharged about 9 h and 30 min after the battery discharge began at 17:38 on 5 November 2019. The discharge power was 1.739 kWh (discharge peak power of 0.199 kW), and the load power at that time was 1.867 kWh. The battery was completely discharged and battery voltage was not maintained until the charge of PV power the next day. The next day's PV power was sent to the load and grid.

Under mode 4, the experiment was conducted for a total of 3 days from 17 to 19 September 2019. The weather was cloudy and sunny. Figure 7 shows the graph of time variations of the daily PV, battery, grid and load power, battery voltage, and battery capacity (SOC) in mode 4. The battery is preferentially charged by PV power, and then by grid power when there is no PV power and the battery voltage reaches the full discharge protection voltage. In other words, if the battery is likely to be discharged, the battery is charged with grid power. The battery started to recharge at 04:03 on 18 September 2019, about 9 h and 30 min after it was first discharged at 18:31 on 17 September 2019. 18 On September 2019, the battery voltage fell at 4:00, but it was not fully discharged due to the charging of the grid power. Based on the 2-day data, the total discharge power was 2.894 kWh (discharge peak power of 0.199 kW), the load power at this time was 2.916 kWh, and the total power charged from the grid was 0.214 kWh.

In the modes where PV power was supplied to the load first (mode 1 and 2), the charge/discharge of the battery is determined by the load. Therefore, charge/discharge may occur frequently and the battery may not be sufficiently charged. As the battery voltage drops rapidly after complete discharge, it is necessary to reduce the battery idle time between discharge and charge. On the other hand, in the modes where PV power was supplied to the battery first (mode 3 and 4), PV power is supplied to the load after the battery is fully charged. The graph of mode 4 (18 September 2019) representatively shows this characteristic. The modes, in which the battery was charged only with PV (mode 1 and 3), risk full discharge in the absence of PV. Therefore, the ability to maintain battery voltage is required to use this mode. If the battery charge sources are PV and grid (mode 2 and 4), the battery is charged by grid power to maintain the battery voltage. The graphs of mode 2 and mode 4 show the charge of the grid power before and after the PV time. Further, in this mode, full discharge did not occur even on the third day of the experiment period.

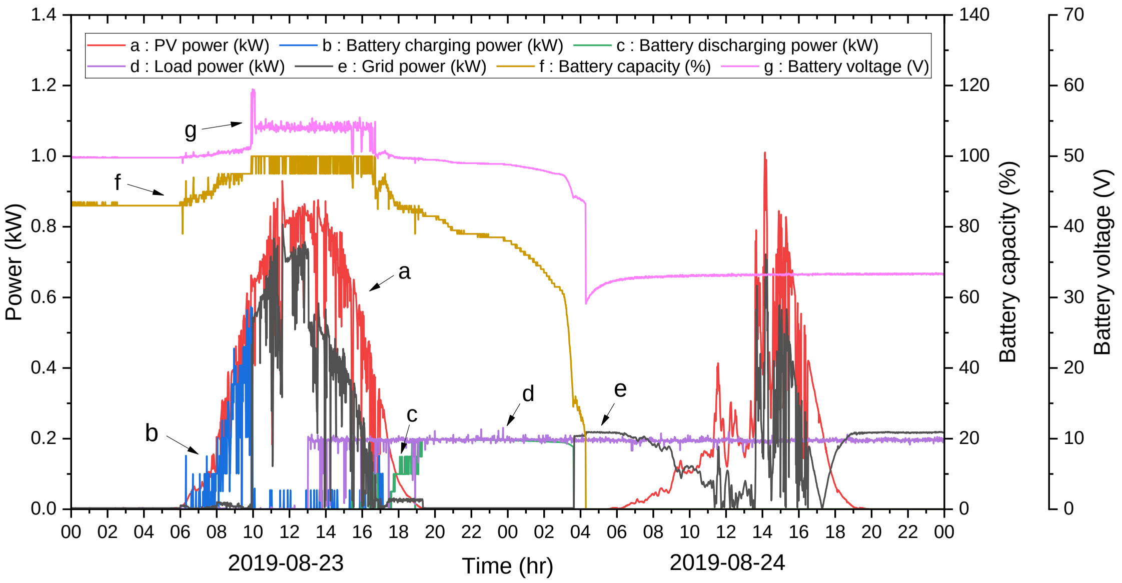


**Figure 4.** Performance characteristics of BESS prototype with balcony PV based on mode 1 (23–24 August 2019).

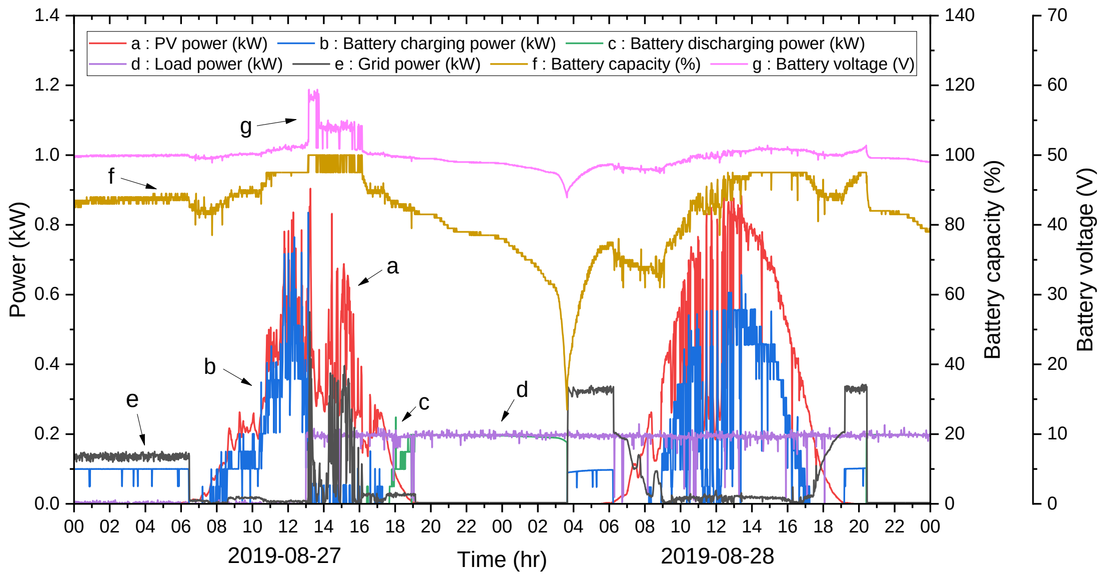


**Figure 5.** Performance characteristics of BESS prototype with balcony PV based on mode 2 (27–28 August 2019).

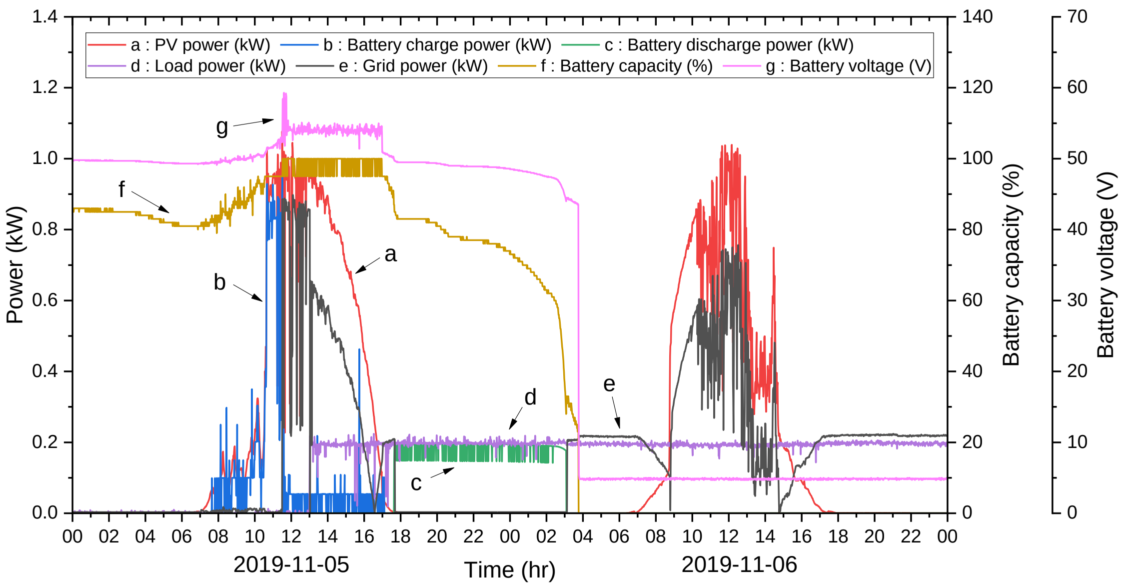


**Figure 6.** Performance characteristics of BESS prototype with balcony PV based on mode 3 (5–6 November 2019).

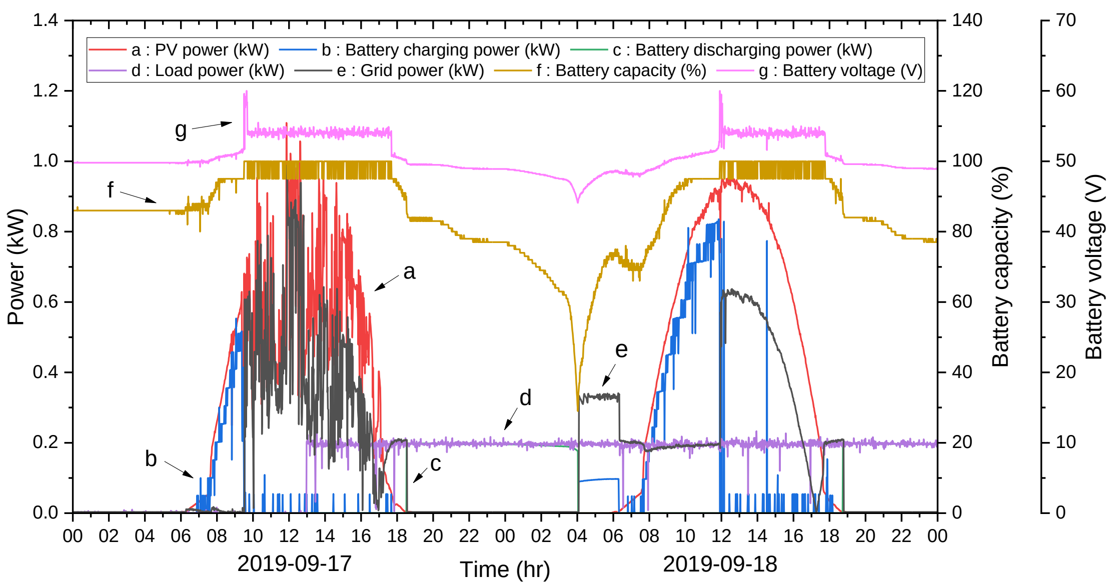


**Figure 7.** Performance characteristics of BESS prototype with balcony PV based on mode 4 (17–18 September 2019).

As an additional experiment, mode 4 was applied by changing the load to an air conditioner (power consumption of 2280 W). The experimental results are shown in Figure 8. The set temperature of the air conditioner was 22 °C, and the actual power consumption was about 1400 W. Based on the PV generation time, it was confirmed that the battery was charged by PV power and discharged to the load.

The operation modes of the residential BESS with the balcony PV were confirmed in individual households of apartment houses through experiments for each operation mode of the residential BESS. The results suggest that mode 4 is the most appropriate among the four operation modes of BESS. Nevertheless, some functions are still required to apply the scheme to individual households of apartments. First, the load connected with BESS should be the total power consumption in the household, not the power consumption of the home appliances connected to a separate load line. When only the balcony PV is installed, the PV power is supplied to the household through the plug of the inverter to reduce the total power consumption. In order to use the residential BESS to reduce total power consumption, such as the balcony PV, it is necessary to integrate the grid and load lines that are currently separated. Second, the battery must maintain the minimum voltage using the grid power before reaching an unusable battery condition. The charge of grid power is a concept that maintains the battery voltage at the minimum current rather than the normal charge. Third, it should be possible to set the voltage range or time for the PV charge. The BESS stops the grid power charge because it recognizes that PV can charge the battery when PV generation starts. However, there is a risk that the battery will reach a full discharge state because the PV power is unstable and cannot maintain a constant charge.

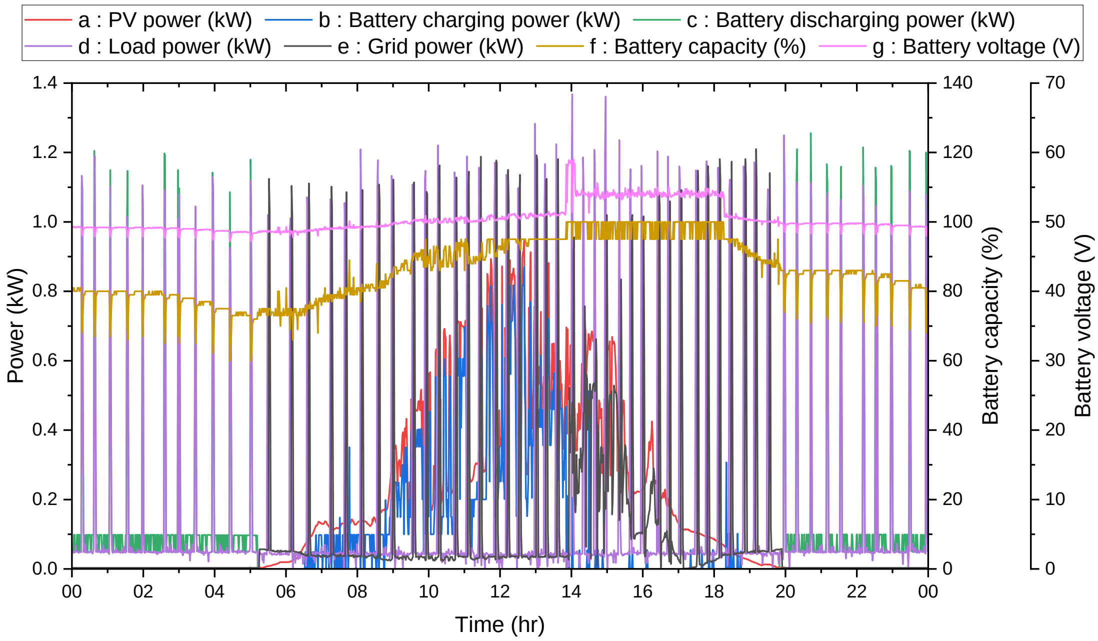


**Figure 8.** Performance characteristics of BESS prototype with balcony PV applied the air conditioner's load (7 July 2019).

## 4. Conclusions

In this study, several experiments were conducted with different operation modes to suggest optimal operation modes of residential BESS with balcony PV in Korea. The experiment apparatuses were a 2.016 kWh BESS, a 1.2 kW balcony PV, and an electric fan. The operation mode of BESS was divided into four types according to PV power supply priority and battery charge source.

The results show that if PV power was supplied to the load first, the charge/discharge of the battery was determined by the load (mode 1 and 2). However, when PV power was supplied to the battery first (mode 3 and 4), PV power was supplied to the load after the battery was fully charged. Furthermore, if the battery was only charged with PV, there was a risk of full discharge in the absence of PV (mode 1 and 3), but charging with the grid prevented this (mode 2 and 4).

Based on the characteristics of each operation mode, it was determined that mode 4, in which PV power preferentially charges the battery and then charges the battery with PV and grid power, is appropriate for the BESS operation mode of individual households of apartment houses. However, some functions need to be added to ensure applicability of residential BESS to individual households of apartment houses in Korea. First, the load connected with BESS should be the total power consumption in the household, not the power consumption of home appliances connected to a separate load line. Second, the battery must maintain the minimum voltage using the grid power before reaching an unusable battery condition. Third, it should be possible to set the voltage range or time for PV charge. By satisfying the above conditions, BESS with balcony PV is expected to be used efficiently for individual households of apartment houses in Korea. Furthermore, it is believed that it will contribute to zero energy in houses by improving the energy independence rate of households.

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**Data Availability Statement:** The data presented in this study are available on request from the corresponding author.

**Conflicts of Interest:** To the best of our knowledge, the named authors have no conflict of interest to declare, financial or otherwise.

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