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An Assessment of the Optimal Capacity and an Economic Evaluation of a Sustainable Photovoltaic Energy System in Korea

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Abstract: The purpose of this study is to conduct an economic evaluation of a photovoltaic-energy storage system (PV–ESS system) based on the power generation performance data of photovoltaic operations in Korea, and to calculate the optimal capacity of the energy storage system. In this study, PV systems in Jeju-do and Gyeongsangnam-do were targeted, PV systems in this area were assumed to be installed on a general site, and the research was conducted by applying weights based on the facility's capacity. All the analyses were conducted using the actual amount of Korea power exchange (KPX) transactions of PV systems in 2019. In order to calculate the optimal capacity of the power conditioning system (PCS) and the battery energy storage system (BESS) according to global horizontal irradiation (GHI), PV systems with a minimum/maximum/central value were selected by comparing the solar radiation before the horizontal plane for three years (2017–2019) in the location where the PV systems was installed. As a result of the analysis, in Jeju-do, if the renewable energy certificate(REC) weight decreased to 3.4 when there was no change in the cost of installing a BESS and a PCS, it was more economical to link to the BESS than the operation of the PV system alone. In Gyeongsangnam-do, it was revealed that if the REC weight was reduced to 3.4, it was more likely to link to the BESS than the operation of the PV system alone.

Keywords: photovoltaic; energy storage system (ESS); economy evaluation; optimal capacity

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1. Introduction

1.1. Background

The response to climate change is a problem that the world must consider together for sustainability, as it has been selected as one of the 17 UN-SDGs (UN-Sustainable Development Goals). Climate change is intensifying with global economic growth. Korea is also emitting a considerable amount of greenhouse gases in the process of achieving rapid economic growth as a developing country. Starting with the 21st Conference of the Parties (COP 21), which was held at the end of 2015, Korea proposed a goal of reducing 37% of greenhouse gases compared to business as usual (BAU) by 2030. Furthermore, in 2020, the National Demarcated Contribution (NDC) aimed at a 24.4% reduction compared to 2017, and a long-term plan was established to achieve zero net emissions by 2050 through long-term carbon development strategies (LEDS). These goals require a significant level of change in the overall industrial structure and energy consumption behavior of the country. Currently, Korea is implementing various energy policies to strengthen energy demand management, improve energy efficiency, foster low-carbon industries, and reduce greenhouse gases, especially in relation to new and renewable energy.

"The current global energy supply and consumption trend is clearly unsustainable," the International Energy Agency said in its 2008 World Energy Outlook (IEA, 2008). This situation is on the verge of deterioration. The IEA predicts that energy demand will increase by 36% by 2035 even if a "New Policy Scenario" that reflects a wide range of policy commitments and plans is announced by countries around the world, including national pledges to abolish fossil fuel subsidies and reduce greenhouse gas emissions (IEA, 2010). This is a big gap from the sustainable path that aims to stabilize the concentration of greenhouse gases in the atmosphere at 450 ppm to suppress the rise in global temperatures to within 2 °C. To overcome this situation, the IEA presented a sustainable emission path that can be achieved by reducing demand through energy efficiency and disseminating low-carbon energy technologies such as renewable energy, carbon capture and storage (CCS), and nuclear power (IEA, 2010).

Interest in alternative sustainable energy systems is rising worldwide as energy supply instability increases due to the depletion of energy sources, correctional instability, the deepening negative effects of climate change, and the spread of nuclear skepticism. Countries around the world are already pursuing sustainable energy strategies to comprehensively respond to various and serious energy issues such as the depletion of energy sources, increased energy demand, intensified energy price volatility, poor environmental quality, health effects, and increased greenhouse gases. In Germany, the UK, Denmark, and Japan, government-supported research institutes are leading research on sustainable energy paths and prospects, while private organizations such as the World Wildlife Fund (WWF), Greenpeace, Alternative Technology Center (CAT), and Eco-institutes have suggested a path to energy transformation. In Korea, energy system transformation has aimed at easing climate change and breaking away from nuclear power plants, and research and the search for energy transformation have become more important in the wake of the Fukushima nuclear accident.

Representatively, in March 2012, the Energy Alternative Forum 2012 held the 2030 Energy Alternative, The European Renewable Energy Association (EREC) and Greenpeace (2012) announced "Energy revolution Korea's Sustainable Energy Outlook". The two reports showed the possibility of achieving a stable energy supply and significant greenhouse gas reduction and cost-effectiveness without the additional construction of nuclear power plants if demand management is strengthened and gas complexity and renewable energy are expanded by using an energy model.

However, these alternative scenarios have some issues, including the reality of demand management, economic feasibility, the supply potential of renewable energy, and the stability of energy supply and demand. Although economic performance and supply potential are the biggest issues, critics say that if the proportion of renewable energy generation, which is highly volatile and intermittent, such as wind and solar power, increases, the balance of power supply and demand will be weakened, or enormous backup power facilities will be required. In addition, solar power generation has the disadvantage of low economic efficiency compared to Korea's nuclear power generation, and thus the economic evaluation of solar power generation is essential for sustainable renewable energy supply.

Recently, as well as the development of solar cells that maximize photoelectric efficiency, many studies have been conducted to reduce solar power generation costs [1,2]. Cost reduction in solar power generation can result from an assessment of the optimal capacity of the ESS. Therefore, research is needed to assess the optimal capacity of the ESS.

1.2. Motivation

Now, there is a wave of change supporting sustainable development around the world. Energy production sites, an important pillar of industrial society, are no exception. This is because existing fossil fuels and nuclear power generation have caused numerous side effects. The transition to a nuclear-free society has begun in Korea. As an alternative to nuclear power generation, wind power and solar power account for an increasing proportion of Korea's total energy, and in particular, solar power generation is the nation's representative renewable energy. Among various renewable energy sources, solar power generation has the highest potential for renewable energy and is considered by experts to be the most optimized renewable energy source for Korea. According to a report on renewable energy in Korea written by Greenpeace, Korea is considered to have better conditions for solar power generation than Germany, which has the biggest development in the solar energy market. In Korea, the entire land is suitable for solar power generation, and the capacity that can be installed is 52 GW. The amount of sunlight is abundant, and the amount that directly reaches the ground is between 1400 and 1600 kWh/m^2 per year. This value is higher than that of Germany, which has an average annual average of 900 to 1200 kWh/m^2.

Measures for power load management and peak management are required due to the instability of renewable energy. As a result, energy storage system (ESS) technology, which is effective in managing power peaks, has been proposed as an alternative. New installations of ESSs worldwide are increasing every year, and rapid growth is expected due to the expansion of policy support from the United States and European countries to secure power grid stability. In the case of the U.S., policies to expand the supply of ESS are being promoted, such as the mandatory installation of ESSs and the inclusion of ESSs in the renewable portfolio standard (RPS). As for Korea, the RPS policy promotes the supply of new and renewable energy. Korea's RPS policy refers to a system that mandates operators of power generation facilities of 500 MW or more to use new and renewable energy to supply a certain percentage of total power generation.

The key power sources for new and renewable energy supply in Korea are PV systems and wind power. Although the supply of wind power has been delayed owing to difficulties in relation to securing locations, licensing, and civil petitions, the use of PV systems is rapidly increasing due to various power plant site developments and installations of various sizes ranging from small to large. Since new and renewable energy power sources generate power based on natural elements, output derating is possible, but output evaporation is uncontrollable. In particular, solar power generation needs a means to supplement power generation during periods of no solar radiation. An ESS linked to a PV system stores solar power generated during the day and generates power in the evening after sunset, thereby reducing the burden of operating the distribution system due to solar power generation during the day. In addition, by supplying it in the evening, a stable operation of the distribution system and the transmission and distribution systems according to the expansion of PV facilities is possible [1–4]. Accordingly, the Korean government promoted a PV-linked ESS supply policy to reduce volatility due to the expansion of solar power generation and to disperse weekly intensive power generation. Furthermore, the introduction of incentives for the power supply of ESSs has led to a rapid increase in supply since 2018.

As of 2019, power generation companies subject to the RPS system in Korea must supply 6.0% of the capacity of power generation facilities as new and renewable energy. By 2023, the ratio should be increased to 10%. At this time, the supply of new and renewable energy can be carried out by obtaining a renewable energy certificate (REC). A REC is a supply certificate certifying that the power generation business has produced and supplied electricity with new and renewable energy facilities. It is issued on a per MWh basis, and the person obligated to supply the renewable energy can cover the number of supply obligations granted by purchasing a REC. In the case of a solar generator (photovoltaic, PV) operating alone, REC weights from 0.7 to 1.5 are imposed depending on the facility capacity and installation location. For issued RECs, transactions are possible within 3 years from the date of issue.

In the case of PV systems linked to an ESS (PV–ESS system), weights of 5.0 in 2019 and 4.0 in 2020 were applied [1]. According to Korean law, the weight is adjusted every three years depending on the environment, the impact on technology development and industrial activation, and the cost of power generation. The weight is expected to gradually decrease based on the analysis that installation costs, etc., will stabilize as the supply of ESSs expands. Therefore, in order to achieve a sufficient economic evaluation due to the reduction in REC weights and ESS installation costs, a multilateral review is necessary. In addition, regulations on the maximum energy charged to the ESS have recently been introduced following the occurrence of an ESS fire, and the continuous decline in REC prices makes it hard for operators who have installed ESSs to operate. The expansion of PV installation can make it difficult to operate the grid network by simultaneously increasing the PV output installed across the country at noon on a clear day with a lot of power generation, so an ESS connection to solve this problem is essential.

Because the ESS is difficult to implement in Korea due to its high installation cost, a weighted policy is currently being implemented, and for this reason, charging and discharging times to which weight is applied have been designated. Prior studies on estimating the optimal ESS capacity have been quantitatively insufficient. First, Lee et al., (2018) [5] analyzed the economic feasibility of the PV–ESS system with the net present value (NPV) technique. As a result, when the PV system capacity is 100 kW, the optimal capacity ratio is 2.28 times, assuming the current installation cost of an ESS, and the payback period is 3 to 4 years long when compared to a single solar system with a weight of 5.0. Furthermore, after analyzing the effect of reducing the installation cost of the ESS in the future, it was found that the optimal capacity ratio is 2.55 times, and the recovery period is 6–7 years when it is reduced below 780,000 won per kWh. This is 2 to 3 years shorter than the current price. Baek et al., (2018) [6] studied the economic feasibility of connecting battery energy storage systems (BESS) to a 100-kW solar power generator installed on the roof of an existing building using REC weights. At this time, the analysis was conducted through the B/C ratio and the NPV. Thus, when a BESS was additionally installed in PV systems, the optimum composition ratio of the power conditioning system (PCS) and battery bank was calculated. In addition, the NPV increased as the capacity increased and then decreased at 90 kW/320 kWh. The optimal PCS capacity was 90 kW, and the battery bank capacity was 320 kWh.

1.3. Literature Review

Choi et al., (2018) [7] conducted a study on the efficiency of a system linking a BESS to a PV system with optimal operation scheduling along with the capacity calculation of the PCS and battery. In order to receive a REC weight of 5.0, the operating method for each section was applied differently. An operation scheduling method that can generate maximum profits was also proposed, and the optimal PCS and battery capacities were calculated through simulation. For the optimal operation scheduling of the battery charging section, whether the BESS was fully charged was determined based on the PV generation amount calculated by predicting solar radiation. Afterwards, the BESS charging time period according to the System Marginal Price (SMP) sales in the section was scheduled. Consequently, it was shown that profit increased in both the charging and discharging periods of the battery. As a result of economic evaluation using the optimal operation scheduling method linked to SMP price when the PV facility capacity is 1 MW, the optimum PCS capacity was 700 kW and the battery capacity was 3 MWh.

Lee et al., (2018) [8] calculated the optimal ESS capacity using the power sales revenue for the Jeju-do area power system by reflecting the ESS REC weight of solar power plants in Korea. For this, it was assumed that an ESS was installed in all solar power generators installed on Jeju Island, and a predicted scenario according to weight change was developed. As a result of developing an optimized model using the General Algebraic Model System (GAMS), the ESS's capacity also increased as the solar power facility capacity increased in the scenario where the weight was kept high. However, the lower the weight, the more profitable ESS was used, but only during the initial planning period.

Oh et al., (2018) [9] suggested that the optimal capacity is when the NPV is the maximum value using the SMP and REC revenue generated from PV–ESS. Gwangju meteorological data and the PVWatts4 program were used to virtually calculate 100 kW of PV power generation. A charge/discharge algorithm was developed by applying the weight application time (charge: 10–16 h, discharge: 16–10 h). As a result of the analysis, when the ESS's capacity was 330 kWh, the NPV showed the maximum value, and when the PCS capacity was 66 kW, the NPV showed the maximum value, suggesting the optimum value.

Currently, the Korean government is actively pursuing a "Green New Deal Policy", and the importance of new and renewable energy is increasing further. Despite the Korean government's solar power supply project and support policies, uncertainty about the economic feasibility of investing in ESS facilities is one of the reasons why it restricts the supply of ESSs in Korea. Among the ESS supply plans, a specific economic analysis of the cost increase in power generation operators due to ESS-connected solar power generation and research on effective ESS introduction are needed. When an ESS is connected to solar power generation, the profit structure should be checked and the facility capacity of the ESS should be estimated to ensure optimal economic feasibility according to these analysis results. In addition, in order to analyze the effectiveness of the support policy for ESS-connected solar power generation, the economic feasibility of solar power alone and ESS-connected generation should be compared.

Because of this importance, a number of studies on the economic evaluation and the capacity calculation of ESSs related to solar power generation have been conducted. However, there are limits regarding the general applicability of the research results, as they were conducted based on solar power generation data for specific regions, not the entire country. There are about 800 solar power plants on Jeju Island, Korea, and the penetration rate is quite high, enough to cover about one third of the electricity consumed by residents. Thus, it would be meaningful to use the results data of this region. Therefore, the purpose of this study is to evaluate the economic feasibility of the PV–ESS system based on the performance data of the amount of solar power generation (PV) in operation in some regions of Korea, and to calculate the optimal capacity of the ESS.

2. Review of ESSs for PV Applications

2.1. A BESS Design for PV Applications

An energy storage system (ESS) is a device for increasing power utilization efficiency and supplying high-quality power by storing power and using the stored power when necessary [10]. That is, it is a system that increases energy efficiency by storing power produced by power plants in a large secondary battery and transmitting additional power when necessary. Therefore, an ESS reserves energy when power demand is lower than the power supply and supplies it at the time when demand is highest or overloaded to increase power quality and improve energy efficiency. In particular, for solar power generation, the amount of sunlight is not constant and sustainable electricity supply is limited. Therefore, it is essential to store electricity in accordance with the utilization of the ESS system. Since the distance between where electricity is produced and where it is consumed is far away, the power system goes through the stages of production, transmission, and distribution. It occurs in most electrical accident power supply systems. In order to solve this centralized power system problem, a smart grid with the characteristics of distributed power has been devised and the energy storage system has made it possible [11,12]. The ESS is largely composed of a battery system and a battery management system (BMS), and the battery management system is in charge of charging/discharging control of the battery and managing the battery state [13,14]. In addition, the generated power includes a Power Conditioning System (PCS) for converting and managing the voltage and frequency of the power according to the system and load characteristics, and an energy management system (EMS) for monitoring and controlling the energy storage system. In other words, the electrical storage device includes a PCS, which is a power conversion unit, a battery, which is a power storage unit storing energy, a power management system (PMS) that monitors and controls the PCS and the battery, and a BMS. An ESS mostly uses secondary batteries, and photovoltaic power generation is operated in connection with a BESS [15–17].

Previous researchers have identified that a BESS can be used to improve the coupling of PV systems [14–24]. According to Zillmann et al., (2011) [18] the use of battery devices to regulate network voltage has been investigated, and various strategies have been applied to control storage device in the study. Recently, many BESS designs connected to photovoltaic power generation have been proposed for residential and commercial PV systems as well as large-scale PV power plant systems [14–24]. The PV-linked BESS design method can be roughly divided into two types as shown in Figure 1: (1) system requirements-based BESS designs and (2) economic analysis-based BESS designs. Based on related previous studies on BESSs, several BESS sizing strategies have been developed for single residential battery storage [23,24]. Figure 1 shows an example of a PV-connected BESS design for residentials.

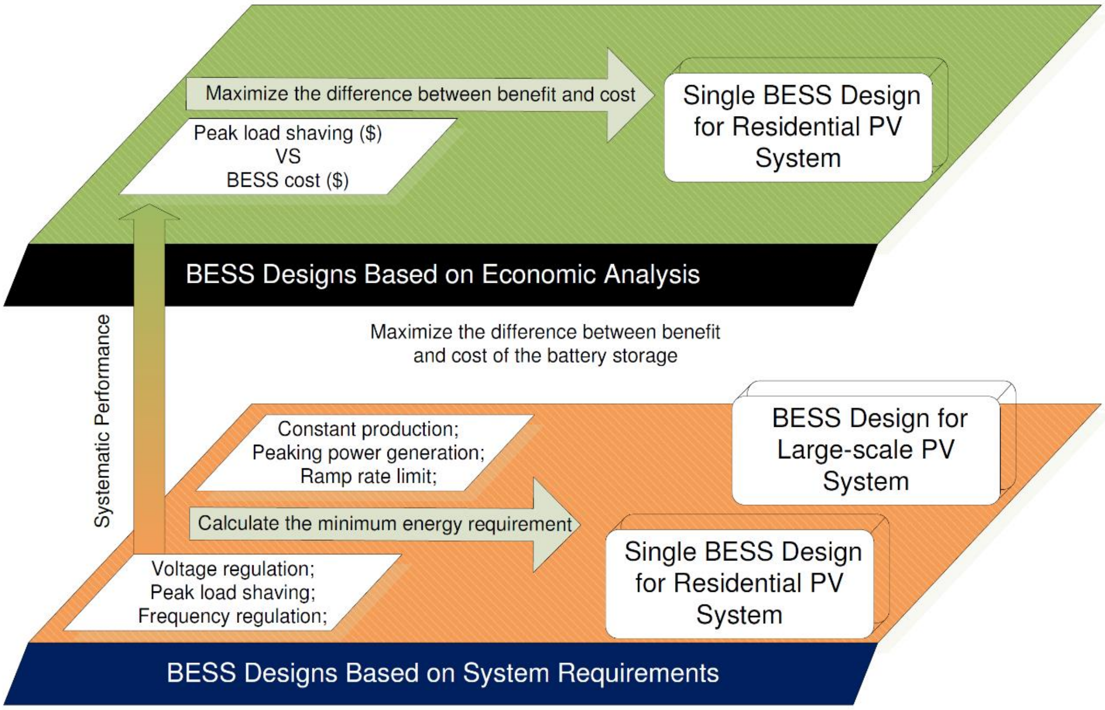

Figure 1. PV-connected BESS designs for residentials [23].

2.2. BESS Design Methods Based on Economic Analysis

In BESS design, a design that considers economic feasibility as much as performance is very important. For an economical BESS design, various cost–benefit sizing methods have been applied [23,24]. To evaluate the most cost-effective battery size, a cost function considering battery lifetime was developed. The electric load and PV power profiles were proposed to assess the economic factors of the battery system and the PV system. However, the prior studies did not consider some factors relevant to BESS sizing on the supply aspect of the electricity distribution system, such as the down-sized workload on voltage regulation modules, or the reduced peaking power generation costs. Moreover, these factors limit the BESS size design and evaluation. The sizing methods described earlier mainly deal with a single BESS with one PV system, so the cost–benefit sizing methods are not suitable for the multiple BESS design which is dispersed everywhere. As a result, the prior methods should be modified and enhanced because the methods lack essential information about the operations of the power system with multiple PV systems and a BESS which are dispersed everywhere.

The design of a BESS is oriented according to the direct functional requirements and the regional needs of the power grid operator and planner. EPRI presents the four-step BESS design direction and proposes sequential design contents. The design contents were basically described from the standpoint of managing the power system and were organized in order to check whether a BESS could be used for locally necessary technologies and to confirm how policy making could benefit owners of a BESS [25]. Choi (2021) suggested improvements in the protection cooperation using a fuse when designing the BESS, improvements in the installation of the fuse for protection from circulating current on the ground side, and improvements in the ability to protect the battery against an increase in constant voltage by checking a potential difference between the ground and the battery neutral point. Combining these functions, a design plan was proposed to protect the entire system by aggregating the protection relay system into the Battery Connection Panel (BCP) [26].

2.3. Dissemination and Operation of a PV-Linked ESS in Korea

Recently in Korea, ESSs have been introduced to alleviate system operation restrictions due to the characteristics of the variable power supplied by solar power generation. Compared to pumped-out power generation with location restrictions, an ESS is installed in demand sites by using high-performance storage batteries that are free from location restrictions and can be installed on a small scale. The purpose of ESS installation in the power plant system is: (1) supply of system operation auxiliary services for generator frequency adjustment, (2) installation and operation in connection with renewable energy to mitigate the volatility of renewable energy, and (3) operation to reduce electricity bills as a means of demand management [27]. In addition, it is used for UPS that supplies electricity in case of emergency such as a power outage, and for supplying starting power for power plants. In order to provide services according to the purpose of use, ESSs are installed according to the purpose of the installation size, location, and operation method, and the calculation of benefits and factors of the ESS also varies according to the operation.

As shown in Table 1, ESSs in Korea increased from 30 MWh (30 locations) in 2013 to 4773 MWh (1490 locations) in 2020, of which 1587 MWh (754 locations) of PV-linked ESSs were established [27]. In particular, 76% of the total supply was concentrated and distributed in 2018. This is because the profitability of operators has improved due to the Korean government's support policy for the PV–ESS by providing weight to REC issue for power supplied by ESS. With the spread of the PV–ESS, there is a big change in the power generation output pattern of PV and PV–ESS companies that are sold through the power exchange. From 2014 to 2017, PV outputs alone were mostly supplied. As a result of the rapid increase in the PV–ESS in 2018, the system supplies due to solar power charging decreased at 10:00, which is the charging time, and power is supplied through ESS in the evening.

As shown in Figure 2, it decreased by 20% based on the maximum output from 70% output to 57% output compared to PV capacity. In other words, the burden on the distribution and transmission networks was reduced. The PV–ESS represents a method of storing power produced from 10:00 h to 16:00 h, when the solar power output is the highest, and generating power in the evening when solar power is not produced. When calculated based on 2017–2020 data, 6 h of PV generation represented about 75% of the daily generation. Therefore, in this study, 75% of daily power generation was calculated as the maximum rechargeable power amount and as the amount of power that can be stored in the ESS.

Currently, the solar charging method in Korea starts at 10:00, as shown in Figure 3, so the ESS-installed solar power is charged at the same time, causing rapid output fluctuations. Therefore, there is a need for a charging control method to improve this.

Table 1. ESS Distribution in Korea (2020).

Item	Linked to Renewable Energy			Demand-Side Management			Total
	PV	Wind	Subtotal	Peak Reduction	Emergency	Subtotal	
Number of Plants	754	24	778	657	55	712	1490
Capacity (MWh)	1587	272	1859	2757	157	2914	4773

Source: Korea Electrical Safety Corp., MOTIE.

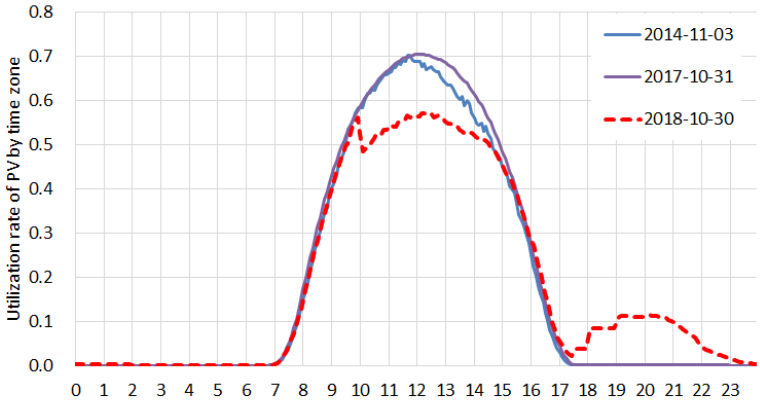

Figure 2. Specific date PV output curve by year for Korea.

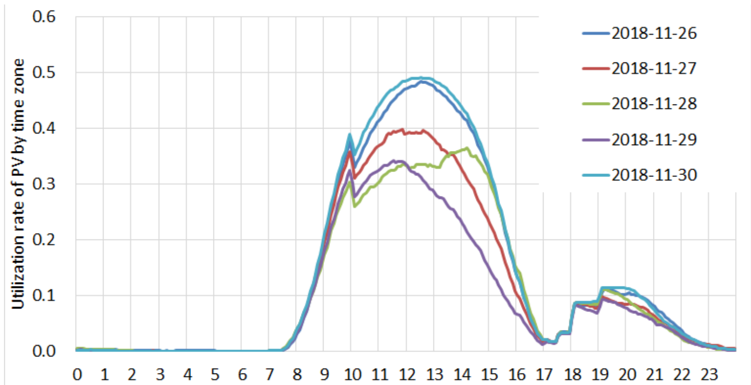

Figure 3. Daily utilization curve variation for Korea (in 2018).

3. Research Method

3.1. Investigation Target and Method

It is very important to check the PV's facility capacity and installation location because the PV system linked to a BESS receives different weights depending on these factors. In this study, a PV system installed on Jeju Island in Korea was targeted, and it was assumed that the system was installed on a general site and weighted according to the facility's capacity.

Of the PV power plants currently traded on the Korea Power Exchange (KPX) in Korea, 43 have a REC weight of 1.2 applied and are less than 100 kW. Moreover, there are 48 PV power plants with a weight of 0.7 applied and exceeding 3 MW. In other words, there are less than 156 PV power plants with a weight of 1.0 and more than 100 kW and less than 3 MW. Therefore, in this study, among 156 PV power plants of 100 kW or more and 3 MW or less with a REC weight of 1.0 applied, power plants with detailed addresses were compared and analyzed by hourly power generation and total insolation on the horizontal plane by time. In this study, the 2019 KPX trading volume of PV systems in operation was used. To calculate the optimal capacity of the PCS and the BESS according to GHI, the total amount of insolation on the horizontal plane for 3 years (2017–2019) in the location where the PV system was installed was compared, and PV systems with minimum/maximum/median insolation was selected.

3.2. PV–BESS System Economics Analysis Method

In the case of the PV–BESS system, it is necessary to analyze the REC weight to secure economic feasibility. Accordingly, an analysis of the economic feasibility according to the presence or absence of BESS installation for PV systems installed on Jeju Island was attempted, along with a calculation of the minimum installation cost of a BESS, which results in economic feasibility due to weight reduction. In this study, it was necessary to calculate the initial generation amount from the PV system because the research was conducted with the assumption that the PV system was newly installed.

The initial power generation of a PV system was assumed to decrease by 0.8% per year based on the year of installation and was calculated by taking into account the operating year (y) up to 2019 using the power generation data. The comparison of economic feasibility according to the presence or absence of BESS installation was conducted using the Levelized Cost of Electricity (LCOE). Since the BESS lifespan was assumed to be 15 years and the PV lifespan was assumed to be 20 years, it was assumed that the PV system operated alone for 5 years when the BESS did not operate.

The prerequisites for the economic analysis of the PV system were data from the Korea Electric Power Exchange, which are research data on the cost of equalizing solar power generation. In this study, the installation cost of a PV system as of 2019 was assumed to be KRW 1,600,000/kW (1368 dollar/kW), and OPEX was assumed to be 2% of CAPEX. In addition, the BESS is charged for 6 h from 10 a.m. to 4 p.m., and the REC weight of 5.0 is applied only to the amount of solar power discharged during the 6 h. Therefore, for solar power generation generated at a time other than the above time, the REC weight was assumed to be 1.0.

4. Research Results

4.1. The Optimal Capacities of the PCS and the BESS According to REC Weight

The study was conducted while increasing the REC weight from 3.0 to 5.0 by 0.5. The PCS capacity increased from 0.1 to 0.8 times the capacity of the PV system and the BESS capacity increased from 0.5 to 5.0 times the capacity of the PV system in 0.1 increments, and two PV cases were analyzed using the MATLAB program. Figure 4 shows flow chart of optimal capacity and the factor of the PCS and the BESS.

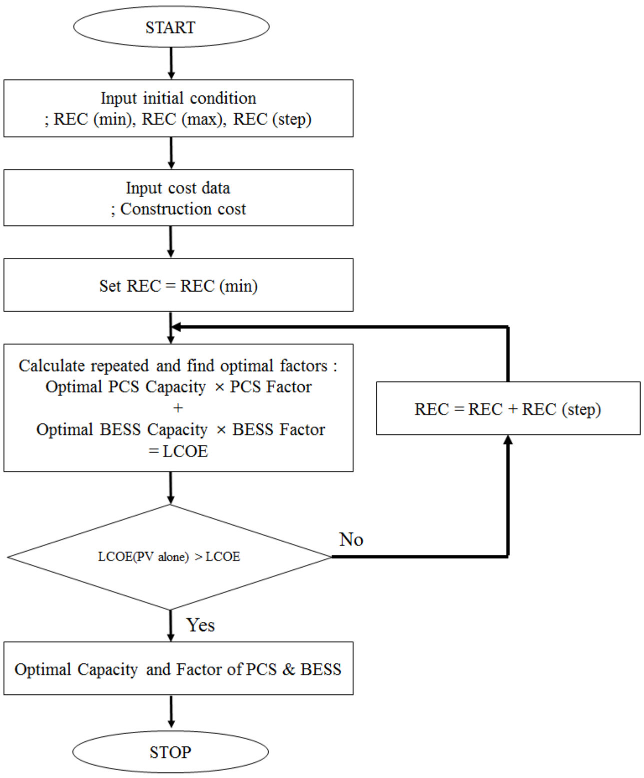

Figure 4. Flow chart of optimal capacity and the factor of the PCS and the BESS.

First, in the case of Jeju Island, when the REC weight was reduced by 0.5 intervals, the cost-effectiveness of operating the PV system was lower than that of Gyeongsangnam-do PV system, and the cost-effectiveness of installing a BESS was high. In addition, when the REC weight was 3.0 or higher, it was economically feasible to install a BESS compared to the operation of the PV system alone. The optimal capacities of the PCS and the BESS are expressed as multiples of PV for easy comparison with PV capacity. With regard to fixing the installation cost, as the REC weight decreased, the economic feasibility of installing the BESS decreased, so the optimal PCS and the optimal capacity of the BESS also decreased (Table 2). For 2.5 or less, it was found that operating the PV system alone was more economical than installing a BESS.

Table 2. Optimal capacities of the PCS and the BESS due to PV and REC weighting factor reduction (Jeju-do in Korea).

REC Weighting Factor	LCOE (Dollar/kWh)	PCS Capacity	BESS Capacity
5.0	0.0977	×0.4	×2.4
4.5	0.1057	×0.3	×1.9
4.0	0.1145	×0.3	×1.8
3.5	0.1225	×0.2	×1.3
3.0	0.1307	×0.1	×0.6

In the case of the PV system in Gyeongsangnam-do, when the REC weight was reduced by 0.5 intervals, it was confirmed through LCOE comparison that the economic feasibility of the PV system operated alone was higher than that of the Jeju PV system. As for installing a BESS, when the REC weight was 3.5 or higher, the LCOE value was smaller than that of the PV system alone, resulting in economic feasibility. When the installation cost was fixed, as the REC weight decreased, the economic feasibility of installing the BESS decreased, so the optimal PCS and the optimal capacity of the BESS also decreased (Table 3). In addition, when the REC weight was less than 3.0, it was found that operating the PV system alone was more economical than installing a BESS.

Table 3. Optimal capacities of the PCS and the BESS due to PV and REC weighting factor reduction (Gyeongsangnam-do in Korea).

REC Weighting Factor	LCOE (Dollar/kWh)	PCS Capacity	BESS Capacity
5.0	0.0816	×0.4	×2.8
4.5	0.0877	×0.3	×2.2
4.0	0.0956	×0.3	×2.1
3.5	0.1023	×0.2	×0.7
3.0	0.1090	×0.1	×0.5

4.2. Analysis of Economic Feasibility According to REC Weight

The optimal capacities of the BESS and the PCS when the REC weight was 5.0 were calculated based on the Korea power exchange (KPX) transactions of PV systems in 2019. In order to analyze the economic feasibility of installing the BESS and the PCS, when the BESS and PCS were 2.74 times and 0.4 times the PV system, respectively, the LCOE of the PV–BESS system and the single-operated PV system according to the REC weight reduction were calculated. In addition, the installation cost of the BESS and the PCS, where economic feasibility occurs, was calculated. On the other hand, in order to calculate the optimal BESS capacity in consideration of the REC weight, it is necessary to analyze the economic feasibility according to the change in the capacity of the BESS, so the LCOE was calculated and proceeded. The LCOE calculated the net present value by discounting the generation amount and cost (construction cost, fuel cost, operation and maintenance costs, etc.) that occur irregularly by year, uniformly by year. LCOE represents the cost of NPV being zero. Given that the LCOE is a nominal value, the future generation and LCOE are calculated to be the same, taking into account the present values of cash flows and cost flows. In this study, LCOE was used to analyze the economic feasibility of reducing REC weights and falling installation costs of the BESS and analyzed the economic feasibility by a comparison with the LCOE of the PV system operating alone. In the above equation, CAPEX includes solar modules, inverters, peripherals (balance of plant, or BOP), BESS, PCS, engineering, procurement and construction (EPC), and other costs. OPEX refers to maintenance/repair costs. T represents the lifetime of the PV system, the BESS, and the PCS, r is the discount rate, d is the degradation factor, and P is the amount of power generation of the solar power generator.

4.2.1. Analysis of Jeju Island

First, the LCOE of Jeju Island with the PV system operating alone is 0.1320 dollar/kWh, so if the LCOE value was smaller than this, it was considered economical. The LCOE according to the weight change of the PV–BESS system is shown in Table 4.

Table 4. LCOE of the PV–BESS systems due to the REC reduction (Jeju-do).

REC Weighting Factor	3.6	3.5	3.4	3.3	3.2	3.1
LCOE (dollar/kWh)	0.1261	0.1287	0.1315	0.1345	0.1371	0.1401

When there was no change in the installation costs of the BESS and the PCS, the BESS linkage was more economical than the operation of the PV system alone when the REC weight decreased to 3.4 (Table 4). On the other hand, when the REC weight decreased to 3.0, 2.5, and 2.0, the LCOE according to the BESS installation was calculated by changing the BESS and PCS installation costs from 90% to 40% of the current installation cost (Table 5).

Table 5. LCOE of the PV–BESS systems due to the reduced installation costs (Jeju-do).

Installation Cost	REC Weighting Factor = 3.0	REC Weighting Factor = 2.5	REC Weighting Factor = 2.0
90%	160.27	180.44	206.51
80%	151.88	171.32	195.82
70%	-	161.90	185.22
60%	-	152.31	174.25
50%	-	-	163.56
40%	-	-	152.87

As a result of the analysis, when the REC weight was reduced to 3.0, economic feasibility occurred when the BESS and PCS installation costs were reduced to 80% of the current installation cost. In addition, when the REC weights were 2.5 and 2.0, economic efficiency occurred when the BESS and PCS installation costs were reduced to 60% and 40% of the current installation cost, respectively.

4.2.2. Analysis of Gyeongsangnam-do

As a result of the analysis of Gyeongsangnam-do, the LCOE of the PV system operating alone is 0.1127 dollar/kWh, so if the LCOE value was smaller than this, it was judged to be economical. The LCOE according to the weight change of the PV–BESS system is presented in Table 6.

Table 6. LCOE of the PV–BESS systems due to the REC reduction (Gyeongsangnam-do).

REC Weighting Factor	3.6	3.5	3.4	3.3	3.2	3.1
LCOE (dollar/kWh)	0.1110	0.1132	0.1158	0.1180	0.1207	0.1234

When there was no change in the installation costs of the BESS and PCS, it was more economical to connect the BESS than to operate the PV system alone when the REC weight decreased to 3.6 (Table 6). When the REC weight decreased to 3.0, 2.5, and 2.0, the BESS and PCS installation costs changed from 90% to 40% of the current installation cost to calculate the LCOE according to the BESS installation, and the results are shown in Table 7.

Table 7. LCOE of the PV–BESS systems due to reduced installation costs (Gyeongsangnam-do).

Installation Cost	REC Weighting Factor = 3.0	REC Weighting Factor = 2.5	REC Weighting Factor = 2.0
90%	142.37	159.81	184.77
80%	135.21	151.44	175.23
70%	-	143.54	165.78
60%	-	135.20	157.50
50%	-	-	148.11
40%	-	-	137.03

As a result of the analysis, when the REC weight was reduced to 3.0, economic feasibility occurred when the BESS and PCS installation costs decreased to 80% of the installation cost used in the study. In addition, in the case of REC weights of 2.5 and 2.0, economic efficiency occurred when the BESS and PCS installation costs decreased to 60% and 40% of the installation costs used in the study, respectively.

5. Discussion

Power demand is on a continuous rise, and facilities must be expanded for a sustainable power supply. However, in the face of difficulties due to environmental problems and the avoidance of nuclear power plants, it is necessary to expand new and renewable energy such as photovoltaic power generation. An ESS connected to photovoltaic power generation is evaluated as a device capable of buffering a system problem if a large-scale power outage or degradation of power quality occurs. In this study, economic feasibility was evaluated by calculating the optimal capacity of an ESS connected to solar power generation in Korea. The role of the ESS is very important for sustainable and stable power supply through photovoltaic power generation, and the optimal capacity of the ESS needs to be accurately evaluated. Previous studies related to solar power have focused on calculating the optimal capacity of the ESS and evaluating economic feasibility. This is because the ESS's optimal capacity calculation and economic evaluation are essential for sustainable power supply through solar power generation.

Zhou et al., (2010) argued that new and renewable energy sources exhibit power generation characteristics according to weather conditions and introduced a system that models the type of weather data and the type of system to estimate power generation and determine the capacity limit of solar–wind–battery systems. The study was conducted to calculate the optimization process of each power source [28]. Belfkira et al., (2011) modeled the wind/solar/diesel system in an independent micro-grid and researched a method of calculating the optimal capacity by applying the DIRECT algorithm, objective function, and constraints, and considering the battery state of charge (SOC, state of charge) [29]. Chen et al., (2013) introduced the technique of calculating the capacity of an ESS by predicting the uncertain power generation probability using the probability distribution function of wind power generation and claimed that the selection of the ESS's capacity can be determined by analyzing cost–benefit [30]. Bludszuweit et al., (2011) claimed that the selection of an appropriate capacity of an ESS in a micro-grid composed of composite power sources such as sunlight, wind power, micro-turbines, fuel cells, and ESSs plays a decisive role in improving the reliability of the micro-grid and found the optimal ESS capacity [31].

In addition, Padaee et al., (2012) proposed a method of calculating the optimal capacity of each energy source from multiple renewable energy sources and reported that the application of multiple energy sources lowers the overall power facility unit price and increases power supply reliability. In addition, a method of obtaining the optimal solution of PV–ESS by applying a genetic algorithm was presented [32]. Ru et al., (2013) conducted a study on the calculation of the optimal ESS capacity of a system linked to grid-linked solar power generation and an ESS. Solar capacity is determined by load demand and is a method of supplying power from the ESS when solar power generation is not available. In this system, a study was conducted to calculate the optimal capacity by considering the maximum economic feasibility of an ESS in a rate system in which power unit prices differ due to power demand. The advantage of this system is that it has the effect of attenuating the maximum power, so the effect of lowering the operating reserve power of the system was also considered. A plan to obtain an economical optimal capacity by comparing the installation unit price of an ESS with the power purchase unit price was announced [33]. Khatib et al., (2016) introduced a method of calculating the capacity of solar power generation facilities and ESSs in a standalone PV–ESS, and considered that technical, economic, social, and political factors play a role in the calculation criteria [34].

6. Conclusions

In this study, the economic feasibility of the PV–ESS system was evaluated based on the performance data of the power generation amount of solar power generation (PV) operating in Korea. Based on the economic feasibility evaluation results, the optimal facility capacity of the ESS was also calculated. The PV system installed on Jeju Island and in Gyeongsangnam-do was the target of analysis in this study, and the analyses were conducted by applying weighting factors according to facility capacity. All of the analyses were conducted using the 2019 KPX trading volume of the PV system in operation. In order to calculate the optimal capacity of the PCS and the BESS according to GHI, the total amount of insolation on the horizontal plane was compared and analyzed for 3 years (2017~2019) at the location where the PV system was installed. The key findings of the analysis are as follows.

(1) In the case of Jeju Island, when there is no change in the installation costs of the BESS and the PCS, and the REC weight decreases to 3.4, it was found that the economic efficiency of connecting the BESS is higher than that of operating the PV system alone.
(2) In Gyeongsangnam-do, when the REC weight decreases to 3.6, it was found that connecting the BESS is more economical than operating the PV a system lone. It was found that when the REC weight decreases to 3.6, the connecting BESS is higher than that of operating the PV system alone.

Environmental problems and sustainable energy are very important in the modern climate crisis era. As this is sustainable energy, solar power can be an alternative. In particular, the Korean government is actively supporting renewable energy, especially solar power. In this work, the optimal capacity of the BESS according to REC weights was determined, but it has the following limitations: First, we proceeded with the assumption that the charging efficiency and discharge efficiency were the same for the BESS used in the study. Second, the factors for reduced REC weights and falling installation costs were not considered in determining the optimal capacity of the BESS. Therefore, further research needs to reflect the exact values of charging efficiency and discharge efficiency of the BESS. In addition, the factors for reducing REC weights and falling installation costs need to be reflected in determining the optimal capacity of the BESS. This study is worthwhile in that it provides an economic evaluation of PV–ESS systems for some of the major solar power regions in Korea and provides a way to increase the efficiency of domestic solar power generation by calculating the optimal capacity of ESS.

Currently, the Korean government has established a long-term plan to significantly increase the proportion of photovoltaic power generation to achieve the carbon neutrality goal. Therefore, this study is expected to contribute greatly to the long-term operation of

Korean photovoltaic power generation in that it evaluated the optimal capacity calculation and economic evaluation for the efficient operation of solar photovoltaic storage systems.

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References

1. MOTIE. Guidelines for Management and Operation for Supply Obligation of Renewable Energy and Fuel Mix: (Appendix 2) Weight by Renewable Energy Source. 2018. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_Market_Southeast_Asia_2018.pdf (accessed on 10 September 2021).
2. Oh, Y.J. Status and prospect of energy storage system (ESS) in Korea. *Hana Industry Info.* **2019**. Available online: http://www.hanaif.re.kr/boardDetail.do?hmpeSeqNo=33893 (accessed on 10 September 2021).
3. Yun, C.S. A study on the estimation of REC multiplier for ESS introduction. *KMAC* **2014**, *23*, 106–111.
4. Lee, W.G.; Kim, K.W.; Kim, B.H. Research on PV-connected ESS dissemination strategy considering the effects of GHG reduction. *J. Energy Eng.* **2016**, *25*, 94–100. [CrossRef]
5. Lee, Y.J.; Kim, S.Y.; Han, S.K. A Study on the Energy Saving Capacity of Solar Power Generation System using Economic Evaluation. *Trans. Korean Inst. Electr. Eng.* **2018**, *67*, 21–26.
6. Baek, M.K.; Park, J.B.S.; Son, S.Y.; Shin, H.S.; Park, Y.K. A Study of Optimum Capacity of Battery Energy Storage System Linked PV. *Trans. Korean Inst. Electr. Eng.* **2018**, *67*, 38–45.
7. Choi, Y.S.; Na, S.Y. A Study on the Optimal Operation According to Appropriate PCS and Battery Capacity Estimation of PV-BESS System. *Trans. Korean Inst. Electr. Eng.* **2018**, *67*, 1174–1180.
8. Lee, S.W.; Kim, H.T.; Shin, H.S.; Kim, T.H.; Kim, W. A Study on the Estimation of Optimal ESS Capacity Considering REC Weighting Scheme. *Trans. Korean Inst. Electr. Eng.* **2018**, *67*, 1009–1018.
9. Oh, S.M.; Kong, J.H.; Lee, W.J.; Jung, J.S. Development of Optimal Energy Storage System Sizing Algorithm for Photovoltaic Supplier in South Korea. In Proceedings of the 2018 IEEE Power & Energy Society General Meeting (PESGM), Portland, OR, USA, 5–10 August 2018; pp. 1–5. [CrossRef]
10. Chung, M.H. Modelling of Solar Irradiance Forecasting using Local Meteorological Data. *KIEAE J.* **2017**, *17*, 273–278. [CrossRef]
11. Jo, D.K.; Kang, Y.H. A Study on the Solar Radiation Estimation of 16 Areas in Korea Using Cloud Cover. *J. Korean Sol. Energy Soc.* **2010**, *30*, 15–21.
12. Wi, Y.M.; Jo, H.C.; Lee, J.H. Economic Comparison of Wind Power Curtailment and ESS Operation for Mitigating Wind Power Forecasting Error. *KIEE J.* **2018**, *67*, 158–164.
13. Lee, W.J.; Jung, J.S. Development of the Optimal Energy Storage System Charging/Discharging Scheduling Algorithm using Load and PV Generation Forecasting. *KIEE Summer Conf.* **2017**, *1*, 56–64.
14. Shin, H.S.; Hue, J.S.; Yun, S.Y. A Study on Sizing of Battery for Effective Operation of Standalone Renewable Generation System. *KIEE J.* **2018**, *67*, 15–20.
15. Hong, J.S.; Chai, H.S.; Moon, J.F. Calculation of ESS Capacity of Industrial Customer through Economic Analysis. *KIEE J.* **2015**, *64*, 273–276. [CrossRef]
16. Kim, S.K.; Kim, J.Y.; Cho, K.H.; Byun, G.S. Sizing and Economic Analysis of Battery Energy Storage System for Peak Shaving of High-Speed Railway Substations. *KIEE J.* **2014**, *63*, 27–34. [CrossRef]
17. Gong, E.K.; Sohn, J.M. An Analysis of Optimal Operation Strategy of ESS to Minimize Electricity Charge Using Octave. *KAIS J.* **2018**, *19*, 85–92.
18. Zillmann, M.; Yan, R.; Saha, T.K. Regulation of distribution network voltage using dispersed battery storage systems: A case study of a rural network. In Proceedings of the 2011 Power and Energy Society General Meeting, Detroit, MI, USA, 24–28 July 2011; pp. 1–8.
19. Hill, C.A.; Such, M.C.; Chen, D.; Gonzalez, J.; Grady, W.M. Battery Energy Storage for Enabling Integration of Distributed Solar Power Generation. *IEEE Trans. Smart Grid.* **2012**, *3*, 850–857. [CrossRef]

20. Xiangjun, L.; Dong, H.; Xiaokang, L. Battery Energy Storage Station (BESS)-Based Smoothing Control of Photovoltaic (PV) and Wind Power Generation Fluctuations. *IEEE Trans. Sustain. Energy* **2013**, *4*, 464–473.
21. Beltran, H.; Bilbao, E.; Belenguer, E.; Etxeberria-Otadui, I.; Rodriguez, P. Evaluation of Storage Energy Requirements for Constant Production in PV Power Plants. *IEEE Trans. Ind. Electron.* **2013**, *60*, 1225–1234. [CrossRef]
22. Su, W.F.; Lin, C.E.; Huang, S.J. Economic analysis for demand-side hybrid photovoltaic and battery energy storage system. In Proceedings of the Industry Applications Conference Thirty-Fourth IAS Annual Meeting, Phoenix, AZ, USA, 3–7 October 1999; Volume 3, pp. 2051–2057.
23. Yang, Y. Optimization of Battery Energy Storage Systems for PV Grid Integration Based on Sizing Strategy. Ph.D. Thesis, Florida State University, Tallahassee, FL, USA, 2014.
24. Riffonneau, Y.; Bacha, S.; Barruel, F.; Ploix, S. Optimal Power Flow Management for Grid Connected PV Systems with Batteries. *IEEE Trans. Sustain. Energy* **2011**, *2*, 309–320. [CrossRef]
25. Zhao, G.; Shi, L.; Feng, B.; Sun, Y.; Su, Y. Development Status and Comprehensive Evaluation Method of Battery Energy Storage Technology in Power System. In Proceedings of the 2019 IEEE 3rd Information Technology, Networking, Electronic and Automation Control Conference (ITNEC), Chengdu, China, 15–17 March 2019; pp. 2080–2083.
26. Choi, I.S. A Study on the Improvement of BESS DC Grid Protection and the Distributed Operating System Design Method. Ph.D. Thesis, Myongji University, Seoul, Korea, 2021.
27. Kim, S.S. A Study on the Profit Analysis of PV Power Generation Based on Economic Assessment of Newly-built Building ESS. Ph.D. Thesis, Konkook University, Seoul, Korea, 2019.
28. Zhou, W.; Lou, C.; Li, Z.; Lu, L.; Yang, H. Current status of research on optimum sizing of stand-alone hybrid solar-wind power generation systems. *Appl. Energy* **2010**, *87*, 380–389. [CrossRef]
29. Belfkira, R.; Zhang, L.; Barakat, G. Optimal sizing study of hybrid wind/PV/diesel power generation unit. *Sol. Energy* **2011**, *85*, 100–110. [CrossRef]
30. Chen, S.X.; Gooi, H.B.; Wang, M.Q. Sizing of Energy Storage for Microgrids. *IEEE Trans. Smart Grid.* **2012**, *3*, 142–151. [CrossRef]
31. Bludszuweit, H.; Dominguez-Navarro, A. A Probabilistic Method for Energy Storage Sizing Based on Wind Power Forecast Uncertainty. *IEEE Trans. Power Syst.* **2011**, *26*, 1651–1658. [CrossRef]
32. Fadaee, M.; Radzi, M.A. Multi-objective optimization of a stand-alone hybrid renewable energy system by using evolutionary algorithms: A review. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3364–3369. [CrossRef]
33. Ru, Y.; Kleissl, J.; Martinez, S. Storage size Determination for Grid-Connected Photovoltaic Systems. *IEEE Trans. Sustain. Energy* **2013**, *4*, 68–81. [CrossRef]
34. Khatib, T.; IIbrahim, I.A.; Mohamed, A. A review on sizing methodologies of photovoltaic array and storage battery in a standalone photovoltaic system. *Energy Convers. Manag.* **2016**, *120*, 430–448. [CrossRef]