Optimal Operation of a Hybrid Power System as an Island Microgrid in South-Korea

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Article

Abstract: The microgrid is a power distribution system that supplies power from distributed generation to end-users. Demonstration projects and R&D regarding microgrids are currently in development in several advanced countries. In South Korea, renewable energy-based microgrid demonstration projects are carried out mainly as island or university campus grids. These R&D efforts aim to popularize microgrid systems in South Korea while considering the limited land availability, which impedes the widespread distribution of photovoltaic systems and the microgrid market’s growth. This study presents a floating photovoltaic system configured as an island microgrid combined with a hybrid power system. The floating photovoltaic system is configured on an idle water body integrated with an existing pumped hydroelectric system. The integration of a current pumped hydroelectric system minimizes a battery energy storage requirement, which compensates for the renewable energy sources’ intermittent power output. We evaluate the optimal power flow of the setup using a reliability index to ensure a stable power supply within the standalone microgrid and maximize the supply power range according to the demand response.

Keywords: demand response; hybrid power system; optimal operation; renewable energy sources; standalone microgrid

1. Introduction

An increase in fossil fuel consumption accompanied by rapid economic growth has contributed to greenhouse gas emissions. Thus, all countries worldwide have a shared sense of crisis with regards to the associated environmental problems due to its effects, as highlighted through the Kyoto Protocol and United Nations Framework Convention on Climate Change. These conventions introduced ecological policies such as emission trading, joint implementation, and the clean development mechanism, specifically designed to lower identified greenhouse gases to target levels. Power generation systems that utilize renewable energy sources consider an alternative to reduce carbon emissions and avoid fossil fuel exhaustion [1–3]. Renewable energy can replace existing energy sources as they depend on natural energy sources that are perpetual and do not deplete. Power generated from renewable energy is primarily sourced from solar, wind, hydro, and geothermal [4–7]. Advanced countries have been developing power generation technologies that use renewable energy sources and pursue various demonstration projects to promote their spread [8–10]. Aside from their abundant sources, photovoltaic (PV) and wind power generation systems have intermittent power supply characteristics and do not provide a stable power output. Thus, the coordination and cooperation of various
Viable energy storage devices should be considered. In recent years, energy storage devices have been used in conjunction with renewable energy sources to reduce the peak load, alleviate output fluctuations, provide an emergency power supply, and facilitate energy prosumers [11–16]. There are various types of energy storage systems (ESSs): mechanical storage systems include pumped hydroelectric systems (PHS), compressed air energy storage (CAES), and flywheels; other types of ESSs have lead-acid, lithium-ion, and fuel cells [17]. The efficiency and longevity of an ESS differ depending on the type. Thus, the specifications of an ESS should be considered when applying it to a particular use case. Recently there have been advances in research on hybrid power supply systems in which conventional power generation is achieved with a renewable energy source due to their advantages [18,19].

In general, many studies on hybrid power supply systems have shown that solar and wind power are the most used renewable energy sources, and the most viable ESSs are fuel cells (hydrogen storage system) and lithium-ion batteries [20,21]. Using these ESS for a hybrid power supply system that is configured for a renewable energy source, microgrid operation can be optimized via a multi-objective optimization function [22–25]. To maximize the microgrid’s operating efficiency, the need to evaluate the renewable energy system’s optimal capacity and ESS is essential [26–28]. In recent years, most research attempts focus on the economic aspect of determining the capacity of resources in the microgrid. These researches were carried out to evaluate the technical and financial aspects of operating microgrid power systems using renewable energy sources [29–31]. Proposed an optimal microgrid model via a particle swarm optimization (PSO) algorithm, leading to the best energy sources and capacity feature configuration [32]. A reliability index needs to be satisfied to ensure the power system’s safety, and this is used as a basis to evaluate the microgrid’s optimal capacity. Reference [33] discusses how the power system’s reliability and stability can be analyzed by considering a microgrid under power outage events. The optimal unit sizing method based on a genetic algorithm (GA) is applied to design and develop a natural microgrid system at Dongfushan Island. Reference [34] proposes an operating strategy and optimization method for microgrids’ sizing via a practical testbed. The authors suggested a significant balance between renewable energy sources and ESS will help improve renewable energy resources. The authors proposed an optimal sizing of the microgrid through a simulation from seasonal to hourly data [35]. In [36], the authors presented a coordinated energy dispatch method for a microgrid system. The proposed microgrid system comprises uncontrollable units including wind turbine, photovoltaic system and ESSs such as battery, heat storage system, ice storage tank, which supply power and heat/cooling energies separately. In [37], the authors investigated optimization approaches to appropriately coordinate some microgrid components considering economic and environmental benefits in cost without considering the critical network operational metrics, e.g., system reliability and power loss during the optimization process.

In [38], the optimal size of the Battery Energy Storage system (BESS)-based PSO method presented the higher performance of the system than the optimum size of BESS based on the analytic method. In conclusion, the proposed optimization method based on frequency control can improve power system stability, grid security, and planning flexibility of the microgrid. Laboratories and institutions can evaluate a system’s capacity by using simulation programs such as HOMER, HYBRID 2, HOGA, PV syst, PV-Design Pro, and INSEL [32,39,40]. The microgrid consisted of the PV, battery, and CHP supply the residential load demand. The optimal microgrid sizing uses the Hybrid Optimization Model for Electric Renewable (HOMER) Pro Microgrid Analysis tool. The optimal microgrid allocation uses multi-objective optimization, including an investment cost, reliability index, and line loss [41].

Although considering the operating characteristics and schedules, the studies mentioned above differ depending on the specific operational purpose of an ESS. The ESS capacities also vary depending on the type. In comparison, the microgrid operation with a pumped hydroelectric system (PHS) and battery as energy storage systems is rare within
the research communities focusing on microgrid operation. Besides, it is challenging to utilize the PHS for the hybrid power system because power resources near customers use PHS. Therefore, it is hard to change the existing generation schedule for producing electricity as a hybrid power system resource. There is a need for research considering the power system’s operation with conventional generations and renewable energy systems to improving the utilization rate of traditional resources.

In this paper, we demonstrate the potential of using conventional power sources in conjunction with renewable energy systems and their operation in a microgrid. This study proposes an optimal sizing and scheduling the hybrid power system, including the pumped hydroelectric system as a conventional power source configured as dispatch generators. The hybrid power system needs a storage system such as a battery to ensure stable power output. However, the cost of the battery is too expensive to use. In this paper, we combine a pumped hydroelectric system with a battery as a storage system. By doing so, the size of the battery can be minimized. Also, the pumped hydroelectric system is mainly used as an emergency generator and relieving the peak load. Therefore, the pumped hydroelectric system’s utilization rate is lower than other power plants, which means the pumped hydroelectric systems are not used efficiently. The pumped hydroelectric system is a generation source of the hybrid power system to improve the existing pumped hydroelectric system’s utilization rate. The scope and case study of the demonstration project is based in South Korea. The idea to generate power by utilizing the water’s idle surface via floating photovoltaic systems is advantageous. The floating photovoltaic system serves as the shortage area solution. The power output is improved by installing the PVs on the water’s surface compared with the conventional photovoltaic system. This study also discusses an integrated operation of battery and PHS in conjunction with the floating photovoltaic system making up a hybrid power system. The range of power supply that meets the reliability criteria for the combined system is evaluated.

The rest of this paper is organized as follows: Section 2 presents the system model and the proposed microgrid using the hybrid power system. Section 3 presents the specific mathematical formulation. Section 4 describes a case study for the proposed hybrid power system using the mathematical formulation, which was conducted in the HAPCHEON practical hybrid power system demonstration project in South Korea. The power generation data of the floating photovoltaic system is derived via the simulation software Solar Pro, and the battery capacity is minimized with MATLAB. The matching rate between the identified power generation and demand is analyzed according to the hybrid power system’s configuration. Section 5 concludes the paper by suggesting the scope of the proposed hybrid power system in terms of the number of households it can supply.

2. Microgrid Modeling

This paper explains and clarifies details for a hybrid power system that uses a photovoltaic system. Because the case study has narrow regional characteristics, we focused on the hybrid power system combined with a floating photovoltaic system, for which there has been little research. The PHS and battery are required for stable power generation by the hybrid power system and to minimize the installation capacity of the ESS, which is still not competitive in terms of price. Figure 1 shows the proposed hybrid power system consisting of a floating photovoltaic system, PHS, and battery. We offer an operational algorithm for the standalone microgrid based on the existing pumped hydroelectric system’s power generation data to minimize the hybrid power system’s marginal cost.
2.1. Floating Photovoltaic System

A photovoltaic system generates power by converting sunlight into electrical energy. Its main components are PV cell modules and a power converter system. A photovoltaic system is advantageous over a wind turbine or small hydropower system, which requires specific site conditions, PV systems can be installed anywhere with high solar radiation with no nearby structures impeding exposure to sunlight, regardless of location and scale. Figure 2 illustrates the constitution of the floating photovoltaic (PV) system. The floating PV system using a floating technology is suitable for distribution in regions with limited land availability. The floating PV system is installed on a water surface such as a lake, which has an additional advantage of improving the power output by reducing the PV module temperature; a high temperature adversely affects the power output by lowering the voltage. Therefore, the power output of a floating PV system is the same as a photovoltaic system’s power output. However, power output is influenced by solar radiation and module temperature equation as in (1) [42]:

\[
P_{\text{floating, PV}} = P_{\text{PV rate}} \times \frac{G}{G_{\text{ref}}} \times [1 + K_t(T + (0.256 \times G)) - T_{\text{ref}}]
\]

where \(P_{\text{PV rate}}\) is the rated power under the reference condition [kW], \(G\) is the solar radiation [W/m\(^2\)], \(G_{\text{ref}}\) is 1000 W/m\(^2\), \(T_{\text{ref}}\) is 25 °C, \(K_t\) is \(-3.7 \times 10^{-3} \text{ (1/°C)}\), and \(T\) is the ambient temperature [10,43]. The floating PV system’s power output is higher than the conventional PV system because the floating PV module has a lower temperature.

2.2. Pumped Hydroelectric System

A pumped hydroelectric system (PHS) is a power generation system that stores water by pumping it from the lower reservoir into the upper reservoir when the market price of power is low and generates power by releasing the reserved water at a high price. It is the most competitive ESS currently, with service life longer than any other system, including

![Schematic representation of the Hybrid Power System](image1)

**Figure 1.** Schematic representation of the Hybrid Power System [29].

![The layout of the floating photovoltaic system](image2)

**Figure 2.** The layout of the floating photovoltaic system [43].
lead-acid, lithium-ion, etc. The two main parts of a PHS are the generator/turbine and pump/motor, which run in the discharging (power generation or supply) and charging (pumping or storage) modes. Power is generated by discharging the water stored in the upper reservoir, which spins the system’s turbines [25,31]. The power output from the turbine in the PHS is calculated by (2):

\[ P_T(t) = \rho \times g \times h \times Q_T(t) \times \eta_T \]  

where \( \rho \) is the density of water [1000 kg/m\(^3\)], \( g \) is the acceleration due to gravity [9.8 m/s\(^2\)], \( h \) is the pumping head [m], \( \eta_T \) is the overall turbine efficiency, and \( Q_T \) is the water flow in discharging mode [m\(^3\) s\(^{-1}\)], respectively.

Equation (3) represents the power consumed by pumping water to generate the electricity in the PHS, where \( Q_P \) is the water flow rate from the lower reservoir [m\(^3\)/s], and \( \eta_P \) is the overall pump efficiency, respectively.

2.3. Battery

There are different types of energy storage devices, such as batteries, flywheels, supercapacitors, and supermagnetic batteries [18,19]. In this study, the lithium-ion battery is considered due to its broad applicability and system efficiency [30,44]. The battery output energy varies according to the charging and discharging modes; when the battery is operating in charging mode, its value is positive. Its value is negative when operating in discharging mode. The amount of internal power in the charging and discharging modes varies according to the charge/discharge efficiency and is expressed as follows:

\[ E_{BESS}(t) = \begin{cases} E_{BESS}(t-1) + \eta_c \cdot P_{BESS}(t) \cdot \Delta t & \text{if } P_{BESS}(t) > 0 \\ E_{BESS}(t-1) + \frac{P_{BESS}(t)}{\eta_d} \cdot \Delta t & \text{if } P_{BESS}(t) < 0 \end{cases} \]  

where \( E_{BESS}(t) \) is the energy-charged and discharged from the battery at time \( t \) [kWh], \( \eta_c \) is the charge efficiency of battery [%], \( \eta_d \) is the discharge efficiency of battery [%], and \( P_{BESS}(t) \) is the power output of battery at time \( t \) [kW]. Equation (4) represents the battery’s stored energy when the battery is operating in charging or discharging mode. The charging and discharging mode are operated by constraint of proposed microgrid operation. There explanation will be mentioned in Section 3.1.

3. Mathematical Formulation

Before the operation, the merit order among power generation sources within the microgrid should be determined to ensure efficiency. The marginal cost of a generator can be used as an indicator for determining the merit order among different power sources; this is the cost per unit of power generated, i.e., the cost ($/kWh) to generate a unit power (1 kWh) to meet demand. While conventional fossil fuel power generation sources incur marginal costs consisting of fuel costs for operating the generator and operation/maintenance (O/M) costs, the marginal cost for renewable energy generation is near zero. Therefore, renewable energy power generation sources are placed higher in the merit order. Combining with the conventional power plants, significantly, PHS and renewable energy systems, new power plants’ construction will decrease.

In the hybrid power system, the merit order of a standalone microgrid operation is determined by minimizing the marginal cost as follows:

\[ F(t) = \min \left( \sum_{i=1}^{l} TC_i(t) \right) \]  

where
The marginal cost of each power source is calculated as follows:

\[
\begin{bmatrix}
TC_1(t) \\
TC_2(t) \\
\vdots \\
TC_i(t)
\end{bmatrix} =
\begin{bmatrix}
u_1(t) & 0 & \cdots & 0 \\
0 & u_2(t) & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & u_i(t)
\end{bmatrix}
\begin{bmatrix}
P_1(t) & 0 & \cdots & 0 \\
0 & P_2(t) & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & P_i(t)
\end{bmatrix}
\begin{bmatrix}
MC_1 \\
MC_2 \\
\vdots \\
MC_i
\end{bmatrix}
\] (6)

The total marginal cost of the hybrid power system is calculated as follows:

\[
TC_i(t) = u_i(t)P_i(t)MC_i
\] (7)

where \(TC_i(t)\) is the total marginal cost of power generation source \(i\) at time \(t\), \(u_i(t)\) is the operation status of power generation source \(i\) at time \([0,1]\), \(P_i(t)\) is the power output of power generation source \(i\) at time \(t\) [kW], and \(MC_i\) is the marginal cost of power generation source \(i\) [$/kWh], respectively.

Equation (8) represents the total marginal cost considering the three power sources shown in the proposed system. Therefore, the merit order within the hybrid power system is determined by each generation unit’s marginal costs [32,33]. The merit order within the microgrid is determined by increasing each power source’s marginal cost, i.e., PHS, floating photovoltaic system, and battery supply, which in turn increases power sequentially to the customer. However, unlike ESSs, the floating photovoltaic system output cannot be easily controlled. The surplus power should precede the power supply according to the determined merit order, which necessitates a higher battery capacity. This makes using the PHS to minimize the battery capacity of the proposed system superfluous. Therefore, we changed the power supply order to end-users within the microgrid to the floating photovoltaic system, pumped hydroelectric system, and battery.

3.1. Proposed Operation Schedule of the Microgrid

First and foremost, customers within microgrids are supplied power from the floating photovoltaic system. The resultant surplus power is stored in the battery, as defined by Equations (9) and (10):

\[
P_{BESS}(t) = \min\left(P_{floating,PV}(t) - P_L(t) \cdot (1 + R), E_{BESS}^{\text{max}} - E_{BESS}(t - 1) / \eta_c\right) \tag{9}
\]

\[
s.t. P_{\text{floating,PV}}(t) - P_L(t) \cdot (1 + R) \geq 0 \tag{10}
\]

where \(P_{PV}(t)\) is the power output of floating photovoltaic system at time \(t\) [kW], \(P_L(t)\) is the power demand at time \(t\) [kW], and \(R\) is the spinning reserve [pu]. The stored power is used efficiently in determining the merit order. When demand exceeds the floating photovoltaic system’s power output, power is injected into the microgrid by the PHS. Because the PHS of an existing source operates according to its original schedule, divided into charging and discharging modes depending on the available water level, the operating plan is maintained if the PHS generates enough electricity for the microgrid. Therefore, we should consider the state of the PHS because of the original operation schedule. Using the power output data of the PHS and its capacity, we can compute the state of the generator(on/off), the energy status (SOC), and charging/discharging energy.

\[
P_{PHS,n}(t) = \min\left(P_{\text{nom}}^{\text{PHS}}, E_{PHS,n}^{\text{max}} - E_{PHS,n}(t - 1) / \eta_p\right) \tag{11}
\]

\[
s.t. u_{PHS}(t) = 0 \tag{12}
\]
where \( P_{PHS,n}(t) \) is the power output of \( n \)th pumped hydroelectric system at time \( t \) [kW], \( P_{PHS}^{\text{nom}} \) is the rated power output of pumped hydroelectric system [kW], \( E_{PHS}^{\text{max}} \) is the maximum energy of pumped hydroelectric system [kWh], and \( u_{PHS}^{\text{sch}}(t) \) is the scheduled operation status of the pumped hydroelectric system at time \( t \) \([0, 1]\), respectively.

The charging mode (pump/motor unit) is calculated by Equation (12). The generator cannot operate in charging mode. The power output of the PHS in charging mode is represented as a positive value, which is calculated by Equation (11):

\[
P_{PHS,n}(t) = \begin{cases} 
-\min\left(P_{PHS}^{\text{nom}} - P_{PHS}^{\text{sch}}, \left(E_{PHS,n}(t-1) - E_{PHS}^{\text{min}}\right) \cdot \eta_T\right), \\
\left(P_L(t) \cdot (1 + R) - P_{\text{floating PV}}(t)\right) \cdot \eta_T \geq P_{PHS}^{\text{nom}} - P_{PHS}^{\text{sch}}, \\
-\min\left(P_L(t) \cdot (1 + R) - P_{\text{floating PV}}(t), \left(E_{PHS,n}(t-1) - E_{PHS}^{\text{min}}\right) \cdot \eta_T\right), \\
\text{otherwise}
\end{cases}
\]

\[s.t. \ u_{PHS}^{\text{sch}}(t) = 1\]  

Equation (14) shows that the power output of the PHS is supplied to the microgrid considering the power demand of the customer:

\[
P_{BESS}(t) = \text{Min}\left(P_L(t) \cdot (1 + R) - P_{\text{floating PV}}(t), \left(E_{BESS}(t-1) - E_{BESS}^{\text{min}}\right) \cdot \eta_d\right)\]

\[s.t. \ P_{\text{floating PV}}(t) - P_{PHS}(t) - P_L(t) \cdot (1 + R) < 0\]  

Suppose the hybrid power system cannot meet the power demand within the microgrid after power is supplied from the floating photovoltaic system and PHS. In that case, the shortage is provided by discharging power from the battery, which is the last power source in the merit order, while considering its state of charge. This is defined by Equations (15) and (16):

\[s.t. \ P_{\text{floating PV}}(t) - P_{PHS,n}(t) - P_{PHS}^{\text{sch}}(t) + P_L(t) \cdot (1 + R) \geq 0\]

\[\text{SOC}_{BESS}^{\text{min}} \leq \text{SOC}_{BESS}(t) \leq \text{SOC}_{BESS}^{\text{max}}\]

\[-P_{BESS}^{\text{nom}} \leq P_{BESS}(t) \leq P_{BESS}^{\text{nom}}\]

Equations (17)–(19) show that there are operating constraints in the microgrid. Equation (17) represents that total power output from generator units should satisfy the total power demand in a microgrid. Equation (18) shows the amount of power charged or discharged in the battery must be between the upper and lower limits of battery capacity.

### 3.2. Power Supply Range of the Microgrid

Based on the resultant values, the number of maximum end-users in each customer sector is determined to satisfy the supply reliability criterion. Finally, the full power supply range of the hybrid power system is calculated. Figure 3 shows the algorithm used to calculate the power supply range within the microgrid according to demand response.
A stable power supply should be ensured if the reliability criterion is to be met. When a renewable energy source is connected to a grid, evaluating and analyzing the impact of its intermittent output characteristics on the power supply stability is essential [19,26,27]. This can be done by analyzing the reliability of the supply performance based on the loss of load expectation (LOLE), which is represented by a probabilistic metric. The size, and shape should be optimized to meet the power demand within a standalone microgrid and satisfy the reliability criterion. The reliability index is calculated according to the number of LOLE hours, and it is defined below:

\[
\sum_{t=1}^{T} \frac{X(t)}{T} \leq \text{LOLE}_{\text{base}} \tag{20}
\]

\[
X(t) = \begin{cases} 
0, & P_L(t) \cdot (1 + R) - \sum_{i} P_i(t) \leq 0 \\
1, & P_L(t) \cdot (1 + R) - \sum_{i} P_i(t) > 0
\end{cases} \tag{21}
\]

where \( \text{LOLE}_{\text{base}} \) is the limited LOLE [h/yr], and \( P_i(t) \) is the power output of power generation source \( i \) at time \( t \) [kW], respectively. The genetic algorithm illustrated in Figure 3 is used to calculate the number of end-users in each customer sector and battery capacity. If the microgrid is operated according to the initial battery capacity, the numbers of end-users in each customer sector that satisfy the reliability criterion are different. Equations (20) and (21) can be used to determine the maximum power supply range of a microgrid based on the hybrid power system to meet the reliability criterion:

\[
\lambda_{\text{BESS}} = \sum_{t=1}^{8760} \frac{|P_{\text{BESS}}(t)|}{S_{\text{BESS}} \times 8760} \tag{22}
\]

\[
s.t. \ P_{\text{BESS}}(t) < 0 \tag{23}
\]

To evaluate the genetic algorithm’s fitness, the capacity of the battery with the highest utilization rate and the number of end-users in each customer sector is calculated as given in Equations (22) and (23). Based on the fitness function as in Equation (22), if the fitness function is higher, the battery’s utilization range in the microgrid is higher. The population
consists of the customer types that partake in the microgrid. Before calculating the fitness function, we assess the reliability in each population. If each population satisfies the reliability level, the fitness function is calculated using Equation (24).

On the other hand, if the reliability level is not satisfied, the fitness function’s value is infinite. The selection stage is processed by the Elitist preserving selection method, where the best group survives to the next step. We exclude cases that fail to meet the supply reliability criterion from the optimal solution groups. Crossover is the stage of generating a second-generation population of solutions from those selected through a combination of genetic operators. By producing a “child” solution using the above methods of crossover and mutation, a new solution is created that typically shares many of its “parents” characteristics. New parents are selected for each new child, and the process continues until a new population of appropriate size solutions is generated. There are some methods in the crossover stage, such as “One Point crossover,” “Multi-Point Crossover,” “Uniform Crossover.” In this paper, we apply the multi Point Crossover” method for the crossover stage. In this paper, the multi-point crossover is used in the process crossover stage.

Using the microgrid demand response makes it possible to expand the power supply range of a supply system. The controllable load in each customer sector should be used for end-user load reduction. The controllable load is possible to transfer power consumption. Unlike, uncontrollable load as the baseload is the standby power consumption including TV, refrigerator, etc. If end-user j needs a load reduction, the potential load reduction is calculated using the minimum diurnal power consumption factor to leave the baseload unaffected:

$$P_{TL}(t) = P_L(t) + P_{extra, L,j}(t)$$  (24)

In the hybrid power system, load reduction is performed to meet the reliability criterion when power is supplied to additional end-users. The amount of load reduction is calculated with the minimum power consumption of the additional end-users of each customer sector(j):

$$P_{LR}(t) = \min \left( P_{floating, PV}(t) - P_{PHS}(t) - P_{BESS}(t) - P_{TL}(t) \cdot (1 + R), P_{extra, L,j}(t) - P_{min, L,j}(t) \right)$$  (25)

where $P_{LR}(t)$ is the deduction of the power required by the load [kW], $P_{extra, L,j}(t)$ is the extra power consumption from sector $j$ at time $t$ [kW], and $P_{min, L,j}$ is the minimum power consumption from $j$ sector [kW], respectively.

4. Case Study

4.1. Basic Setting

To build a microgrid based on the hybrid power system, a floating photovoltaic system on an idle water surface is used given the limited land availability in South Korea. For the case study, we resorted to the HAPCHEON hydroelectric power plant developed for the floating photovoltaic power generation demonstration project of HAPCHEON, South Korea. This program has been underway at the HAPCHEON reservoir since 2011 to realize energy self-sufficiency for the country through renewable sources. Floating photovoltaic installations on HAPCHEON Reservoir was launched in 2018. We set up a standalone microgrid supply power to end-users (households) in the residential, agricultural, and educational sectors of HAPCHEON, where the HAPCHEON hydroelectric power plant is located. Table 1 presents the number of end-user households in each customer sector and the average monthly power demand per household. The data were provided by the Big Data Center run by Korea Electric Power Corporation (KEPCO). Table 2 presents the already known facility capacities of the floating photovoltaic system (under development) and the PHS (current in operation) when integrated into the hybrid power system [45]. The PHS in South Korea usually has a storage system comprising at least two to four generation units.
Table 1. Primary data of end-users for each customer sector in HAPCHEON.

| Customer Sector | Residential Sector | Agricultural Sector | Educational Sector |
|-----------------|--------------------|---------------------|-------------------|
| Number of end-user households | 27,300 | 11,460 | 50 |
| Avg. power demand per household [kWh/month] | 163.67 | 889.77 | 7727.80 |

Table 2. Composition of the hybrid power system.

| Power Source | Facility Capacity | Specifications |
|--------------|-------------------|----------------|
| Floating PV system | 40 [MW] | Q cells Q Pro L 300 W |
| Pumped hydroelectric system (PHS) | 50 [MW] | η_T, η_P: 0.85 |
| Battery | Case 1 | 85.379 [MWh] |
|          | Case 2 | 85.122 [MWh] |
|          | η_T, η_P: 0.96 |

We choose the major customer sectors as residential, agricultural, educational customer in this case study. Compare with the biggest area in South Korea, target site of case study is rural area.

Figure 4 illustrates the monthly power demand pattern in each customer. Figure 4a–c represents the residential, agricultural, and educational customer, respectively. In this case study, the power demand is considered by the average monthly power demand and the number of end-user households. We estimated the floating photovoltaic system power generation output based on the solar radiation at the site with the PV simulation software Solar Pro. The same installation angle (latitude +10°) as the ground photovoltaic system was applied under the assumption that the floating system would have a 10% higher power yield compared with the ground system [46].

![Figure 4. Average monthly power demand.](image)
Figure 5 illustrates the average major monthly floating photovoltaic system output. The total amount of the power output is the biggest in May. On the other hand, the total amount of the power output is the lowest in December in Figure 5.

The PHS in South Korea usually has a storage system comprising at least two to four generation units. In this study, the standalone microgrid’s expected efficiency was maximized under the assumption that the HAPCHEON hydroelectric power plant used the PHS described previously with the same capacity. The battery capacity is calculated by Figure 3. Moreover, we determined the supply reliability index at 0.3 [days/yr] LOLE (i.e., the national standard) by using the genetic algorithm to calculate the power consumption pattern of each customer sector, the merit order of the power sources comprising the hybrid power system, and the power supply [47].

The case study was conducted as two sub-studies to compare the effects of integrating the PHS in the hybrid power system and thus varying the power generation source composition. In Case 1, the power system consisted of the floating photovoltaic system and the battery. In Case 2, the power system consisted of the floating photovoltaic system, PHS, and battery.

4.2. Optimal Results

The initial battery capacity for the hybrid power system operation was set at full-capacity mode. The battery in the hybrid power system operates as a charging and discharging mode between 20% and 100% of battery capacity. By combining the PHS, the battery size can be reduced compared with no PHS in Table 2. We set the number of end-users (households) in each customer sector to be equal to the total number of homes, as presented in Tables 1 and 2. We limited the number of end-users to the existing customer sizes by sector to calculate the power supply range.

Figure 6 illustrates the operating schedule of a standalone microgrid consisted of a floating photovoltaic system and batteries. Figure 6a,b and Figure 6c,d present the operating schedule of the microgrid in summer and winter. Figure 6a,b illustrate each units’ hourly power output and the amount of energy in the battery, respectively. In Figure 6a, the surplus power is produced from the floating photovoltaic system after supplying energy to end-users. Therefore, the battery is operating in charging mode when the surplus power is produced in the microgrid. Between 13:00 and 17:00, the battery does not have any capacity for charging the surplus power in Figure 6b. Therefore, we confirm the battery’s power output is not operating at that time in Figure 6a.

On the other hand, the floating photovoltaic system cannot supply the energy to the end-users, so the battery is operating in discharging mode from 01:00 to 07:00 and from 17:00 to 24:00. Figure 6c,d present each unit’s hourly power output and the total amount of energy in the battery in winter, respectively. Compared with the power output of floating photovoltaic systems in summer, winter’s power output is lower. Therefore, the amount of surplus power in winter is lower than in summer. As we can see the Figure 6b, the amount
of the battery’s stored energy reaches the full quickly rather than Figure 6d. Table 3 presents the optimum number of customer households to meet the supply reliability criterion when the microgrid power generation sources are the floating photovoltaic system and battery.

![Figure 6](image.jpg)

**Figure 6.** Operating characteristics of the microgrid without PHS (Case 1).

**Table 3.** The number of optimal customer households within the standalone microgrid (Case 1).

| Customer Sector           | Residential Sector | Agricultural Sector | Educational Sector |
|---------------------------|--------------------|---------------------|--------------------|
| Number of end-user        | 6483               | 1546                | 1                  |
| households                |                    |                     |                    |

The number of optimal households in each customer sector in case 1, residential customers are 6486 households, agricultural customers are 1564 households, and educational customer is only 1 household. The total power demand pattern from Table 3 is almost equal to the power output pattern from floating photovoltaic systems and batteries in case 1.

Figure 7 illustrates a standalone microgrid’s operating characteristics consisting of a floating photovoltaic system, battery, and PHS. Figure 7a,b and Figure 7c,d present the operating schedule of the microgrid in summer and winter, respectively. Figure 7a,b show each units’ hourly power output and the amount of energy in the battery, respectively. When PHS is not producing power, it operates in pumping(charging) mode as derived from its operating schedule. On the other hand, if PHS is using in generating mode, it generates electricity during its active schedule. While in generation mode, the PHS serves energy to customers partaking in microgrids and conventional customers. In Figure 7a, the floating photovoltaic system does not produce the battery steps to operate in discharging mode from 01:00 to 05:00. After 06:00, the surplus power is stored in the battery for 5 h. When the battery is fully charged, further charging is disallowed unless discharging mode. If the
power demand is not satisfied by the floating photovoltaic system, the PHS is available to fulfill the shortage of power, and it generates the electricity from 16:00 to 18:00. However, it is unavailable, as we can see Figure 7a at 19:00. Thus, the battery operates in discharging mode. Consequently, the power demand is satisfied by the battery. Figure 7b presents the cumulated amount of stored energy according to the charging and discharging mode.

![Figure 7. Operating characteristics of the microgrid with PHS (Case 2).](image)

Table 4 presents the optimal number of customers in households to meet the supply reliability criterion when the microgrid power generation sources is comprised of the floating photovoltaic system, battery, and PHS. The number of optimal households in each customer sector in case 2, residential customers are 8400 households, agricultural customers are 969 households, and educational customer is only 43 household. Compare with case 1, the number of residential and educational customers increases significantly. However, the number of agricultural customers decrease about 1.5 times.
Table 4. The number of optimal customer households within the standalone microgrid (Case 2).

| Customer Sector | Residential Sector | Agricultural Sector | Educational Sector |
|-----------------|--------------------|---------------------|--------------------|
| Number of end-user households | 8400 | 969 | 43 |

Figure 8 illustrates the hourly power demand according to the customer’s optimal number from each sector in case 1 and case 2. Figure 8a,b present the total power demand pattern in summer and winter. By using the PHS, the amount of the power demand increases significantly. Although the number of agricultural customers decreases, provided total power demand is increased. Furthermore, the microgrid resorts to demanding a response to expansion the power supply range. We analyzed each customer sector’s power consumption pattern in association with the additional power supply and calculated the potential load reduction per additional customer household to satisfy the reliability criterion through load reduction. The seasonal and diurnal differences in power consumption patterns in each customer sector led to differences in the number of maximum additional customer households to satisfy the reliability criterion and the corresponding total power consumption patterns. The load reduction is calculated via (25) and (26).

![Hourly power demand in each case study.](image_url)

Figure 9 illustrates the variation in the reliability index according to the number of customers in each sector from case 1. Figure 9a–c presents the reliability index of the number of residential, agricultural, and educational customers, respectively. When we use the demand response, the other available number of the customers in each sector considered the constrained reliability index. The reliability index \((LOLE)\) should be in 7.2 h/year (0.3 days/year). The additional available number of residential customers is 54, which satisfies the reliability index. Above 55 customers, the reliability index exceeds the value of the constraints. In the agricultural sector, nine customers are additionally available in this case 1. Finally, only one customer is available in the educational sector.

Figure 10 illustrates the variation in the reliability index according to the number of customers in each sector from case 2. Figure 10a–c present the reliability index of the number of residential, agricultural, and educational customers, respectively. Case 2 should also satisfy the reliability index constraints. The available number of residential customers is 319, which is met by the reliability index. In the agricultural and educational sector, 58, 7 customers are available respectively.
Figure 9. Reliability index according to the number of customers in each sector (Case 1).

Figure 10. Reliability index according to the number of customers in each sector (Case 2).
Table 5 presents the number of additional available customers in each sector in case 1 and case 2. Using the PHS leads to a significant impact on the microgrid through the expansion of the power supply range using the demand response. When operators of this microgrid expand the power supply range, they should consider the microgrid circumstance by choosing the customer sectors that should be added to the microgrid.

Table 5. The optimal number of added customer sector in Case 1 and Case 2.

| Customer Sector Households (No.) | Residential Sector | Agricultural Sector | Educational Sector |
|---------------------------------|--------------------|---------------------|-------------------|
| Case 1                          | 54                 | 9                   | 1                 |
| Case 2                          | 319                | 58                  | 7                 |

4.3. Discussion

Before considering the demand response, the number of customers in each sector was calculated based on the power demand and power output. The power reliability must be satisfied with the reliability standard. Subsequently, when the demand response is considered, the amount of demand that can be reduced for each sector was calculated, and based on this, the additional number of customers was proposed. Since the pattern of power consumption by customer sectors varies by season and time, the maximum number of additional customers who meet reliability standard and the total pattern of power consumption accordingly differ. Considering demand response, it can provide more power to customers as well as reduce surplus power. The matching rate is calculated as ratio of total power output and total power demand. The matching rate of 100% means that the power output is not wasted, but supplied entirely to the power demand. This rate differ depends on operation of demand response. Without considering demand response, the matching rate is approximately 97%. However, the matching rate is higher as 98% than no demand response.

5. Conclusions

This study developed a standalone microgrid capable of supplying stable power to end-users integrating a floating photovoltaic system on an idle water surface. A PHS integrates a battery and pumped hydroelectric system as ESSs to compensate for the intermittent power output characteristics of renewable energy sources. We demonstrated that the battery capacity could be minimized to mitigate the main downside of batteries (i.e., low price competitiveness). By operating the proposed microgrid, nearby areas are supplied electricity independent of the grid. Moreover, existing PHS is integrated into the microgrid, leading to improving the PHS utilization rate. We calculated the maximum power supply range of the microgrid for the system’s supply reliability index to be satisfied by using demand response. The proposed hybrid power system sets up a standalone microgrid supply power to end-users and surrounding areas. This study’s results can serve as a basis for future research on grid reliability to develop methods to improve cost-effectiveness and recover losses. Besides, the hybrid power system can be used to build technology for supplying power reliably and robustly enough to meet the demand of nearby regions. Reducing or removing the hybrid power system’s uncertainty in a smart grid environment will promote the spread of renewable energy use.

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