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# Comparative Analysis between the Government Micro-Grid Plan and Computer Simulation Results Based on Real Data: The Practical Case for a South Korean Island

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**Abstract:** Greenhouse gas (GHG) emissions, which are produced through the combustion of fossil fuels, cause climate change. Unfortunately, South Korea is highly dependent on fossil fuels because of its industrial nature. However, many islands in South Korea have the potential to generate a considerable amount of renewable energy, which should be studied. KEPCO (Korea Electricity Power Corporation), which runs micro-grid facilities in Gasado Island in Jindo, South Korea, built micro-grid facilities in Mozambique in 2015. The micro-grid construction of Gasado Island is considered one of the most successful micro-grid projects of KEPCO, so KEPCO is hoping to expand energy development overseas and become a top-tier global power company. This study aims to find a more technologically and economically optimal hybrid energy system for Gasado Island that KEPCO should have built. We also compared this optimal solution to the Korean government plan. The Korean government plan is the same as the KEPCO plan because KEPCO is classified as a market-oriented public corporation under the Act on the Management of Public Institutions. In the final section of this paper, both the implications and limitations are discussed in detail.

**Keywords:** hybrid energy; HOMER simulation; government plan; comparative analysis; micro-grid; economic feasibility

## 1. Introduction

Due to several energy-related accidents, including the global oil crisis and the Fukushima nuclear plant accident, future energy plans, including green growth and sustainable development, have been considered an essential concept for the prosperity of every nation [1–4]. In accordance with this global trend, a large number of developed countries have placed emphasis on energy security for their plans and policies, including renewable energy development [5–7]. Because the use of household electric appliances has increased, especially air conditioners and heaters, there has been a sharp increase in demand for electric power, especially in industrialized nations. Experts have warned that fossil fuels are becoming more expensive and will eventually run out [8]. Renewable energy generation (including hybrid energy generation) is the inevitable future because of pollution, climate change, and eventual oil depletion [9]. Another important attribute of a renewable energy system is that it can help generate and supply sustainable electric power [10–12]. Thus, the governmental interest in renewable energy is increasing all over the world, including South Korea. Especially as interest in renewable energy grows, the U.S. government's energy policy has evolved as a renewable portfolio standard has expanded [13,14].

Recently, the demand for renewable energy has continuously increased in South Korea due to the inflation of fossil fuel prices and the preparation for the legal obligation of reducing carbon emissions that will soon come into effect [11,15]. Therefore, in South Korea, people tried to introduce renewable energy systems into public buildings like elementary schools and residential areas [16,17]. However, such renewable energy projects always have problems with economic feasibility and business value. Most renewable energy projects usually have relatively low amounts of subsidies and political support. For sustainable development, operating renewable energy businesses with affordable economic feasibility is important.

The Jeollanamdo provincial government, which is interested in renewable energy and micro-grids in South Korea, held a ceremony for the completion of the nation's largest "Jindo-Gasado Micro-Grid System with Hybrid Energy". The Jeollanamdo provincial government, the Jindo country office, the KEPCO (Korea Electricity Power Corporation) research institute, and the Jeollanamdo Technopark cooperated to build a hybrid system including 320 kW of PV (photovoltaic) power, 400 kW of wind turbine power, and 3 MWh of energy storage at government expense, costing approximately 9 million dollars [18]. The size of each device was decided by KEPCO and based on the Electricity Act.

Much research has discussed the economic feasibility of combinations of renewable energy [19–22]. These references are generally based on computer simulation tools using real data sets, such as climate information, real diesel prices, installation and replacement costs, and load profiles [23,24]. However, they generally focus on the potential of sustainable energy for businesses [25] or the necessity of using renewable energy in urban areas [26]. Little research has examined the feasibility of a hybrid system including renewable energy, which can be applied in practical circumstances and provide significant academic and practical insight by using empirical data. Therefore, this study aims to investigate an optimized hybrid system including renewable energy for Gasado Island in South Korea by using its electricity load profile, and we compare this optimization result with KEPCO's already built micro-grid. Additionally, this study analyzes economically, technologically, and environmentally friendly feasible solutions for Gasado Island based on local weather conditions. In addition, the results consider solar radiation on inclined surfaces for the installation of PV systems and variations in wind energy as important factors. Research results include the optimal capacity of PV, wind turbines, and other devices for a hybrid system, which are determined by computed simulation. Optimized hybrid systems satisfy an average daily electric load and consumption during the project time and minimize both the COE (Cost of Energy) and the NPC (Net Present Cost) to set up. This study employs the HOMER (Hybrid Optimization Model for Electric Renewables) to suggest the most optimized hybrid system based on the relevant economic parameters: the COE and the NPC. Based on simulation results, this study aims to investigate the following research questions:

(1) Can the implementation of a hybrid system be an adequate and reliable option for electrification in Gasado Island?
(2) Is the hybrid energy supply built by KEPCO offering the most economically and environmentally practical solution?

## 2. Case Study Description

There are many studies about hybrid power systems providing solutions to energy security problems. Many researchers have dealt with downtown areas and islands [27,28]. Recently, there also has been research on green islands and their influence on both energy independence and hybrid power systems in Southeast Asian countries, especially in South Korea (Table 1) [29–45].

**Table 1.** Studies about hybrid or renewable power systems.

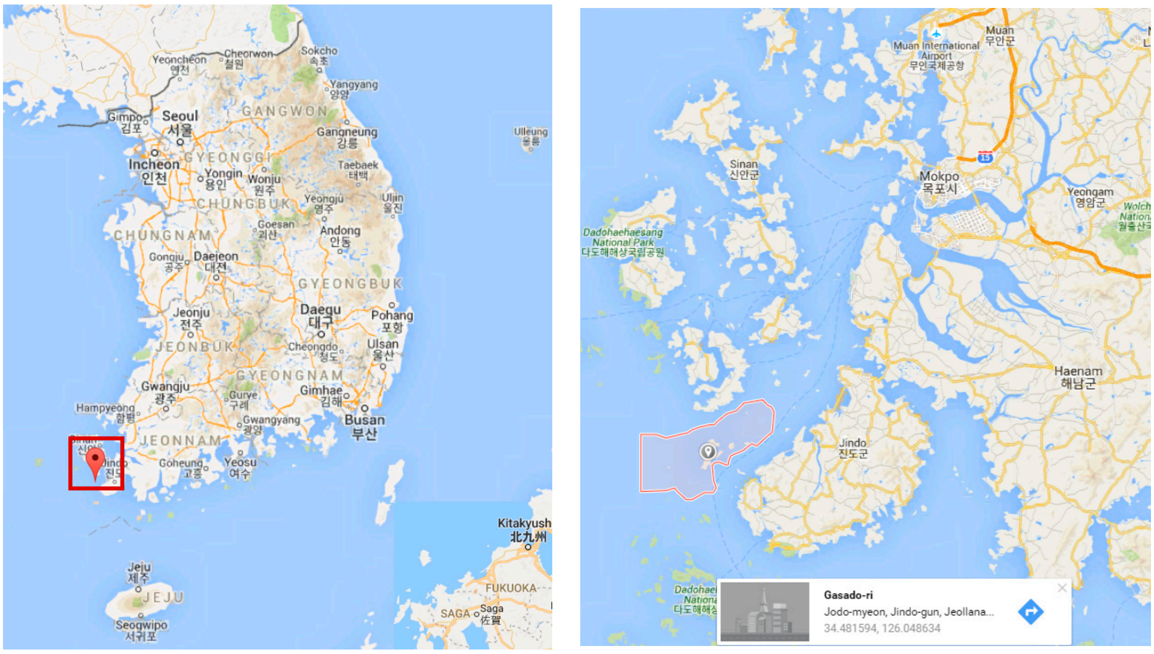
| Author | Title | System Configuration | Analytic Points |
|---|---|---|---|
| Baek et al. (2016) [29] | Optimal renewable power generation systems for Busan metropolitan city in South Korea | PV-WT-Battery-Converter | Using the hybrid renewable energy system in Metropolitan city with 100% of renewable fractions. |
| Karakoulidis et al. (2011) [30] | Techno-economic analysis of a stand-alone hybrid photovoltaic-diesel-battery-fuel cell power system | PV-Battery-Converter-DG | Complementary relationship between DG and PV, cost problems of hydrogen gas and the amount of diesel used. |
| Asrari et al. (2012) [31] | Economic evaluation of hybrid renewable energy systems for rural electrification in Iran—A case study | DG-PV-WT-Battery-Converter | Various standards, such as NPC, COE, RF, maximum distance, cost change of other fossil fuels, $CO_2$ Emission analysis. |
| van Alphen et al. (2007) [32] | Renewable energy technologies in the Maldives—determining the potential | PV-WT-Battery-Converter | Capacity of PV: all day or 35% a day, Fixed cost of electricity was assumed, HOMER algorithm. |
| Shaahid & Elhadidy (2008) [33] | Economic analysis of hybrid photovoltaic-diesel-battery power systems for residential loads in hot regions—A step to clean future | DG-PV-Battery | Complementary relationship between DG and PV, various RF scenarios, Trade-off between COE and RF. |
| Ngan & Tan (2012) [34] | Assessment of economic viability for PV/wind/diesel hybrid energy system in southern Peninsular Malaysia | DG-PV-WT-Battery-Converter | Potential of PV, WT, and DG. Simulated 7 different system configurations. NPC, COE, excess electricity produced, reduction of $CO_2$ emission. |
| Hafez & Bhattacharya (2012) [35] | Optimal planning and design of a renewable energy based supply system for microgrids | DG-PV-WT-Battery-Micro hydro-Grid-Converter | Optimal design, planning, sizing, GHG emissions, break-even point, and the greatest number of cases analyzed. |
| Kusakana & Vermaak (2013) [36] | Hybrid renewable power systems for mobile telephony base stations in developing countries | DG-PV-WT-Battery-Converter | Rural mobile phone stations using PV and WT, Comparative study between hybrid energy system and renewable energy system based on NPC, COE. |
| Ashourian et al. (2013) [37] | Optimal green energy management for island resorts in Malaysia | DG-PV-WT-Battery-Converter-FC-Electrolyzer-Hydrogen Tank | Sensitivity for NPC and GHG emissions, Charge and discharge of ESS, Generating principle of PV panel, Grid-parity between RE and Diesel. |
| Dorji et al. (2012) [38] | Options for off-grid electrification in the Kingdom of Bhutan | DG-Battery | Failed cases, such solar home systems and micro-hydro plants, Sensitivity analysis. |
| Jun Chen & Cristian Rabiti (2016) [39] | Synthetic wind speed scenarios generation for probabilistic analysis of hybrid energy systems | Nuclear-WT-Battery | The effects of installation of various sizes of batteries in reducing renewable variability. |
| Kim et al. (2016) [40] | Comparative Analysis of On-and Off-Grid Electrification: The Case of Two South Korean Islands | Grid-PV-WT-Battery-Converter | Comparative study between two research areas about on/off grid configuration and energy mix. |

**Table 1.** *Cont.*

| Author | Title | System Configuration | Analytic Points |
| --- | --- | --- | --- |
| Baek et al. (2016) [41] | Optimal Hybrid Renewable Airport Power System: Empirical Study on Incheon International Airport, South Korea. | Grid-PV-Battery-Converter | Analysis of changes in energy mix and economic feasibility of hybrid energy system as the airport expands. |
| Jun Chen & Humberto E. Garcia (2016) [42] | Economic optimization of operations for hybrid energy systems under variable markets | Grid-Renewables-Battery-(Primary/ Auxiliary)Heat Generation | Methodology for operations optimization to maximize their economic value based on predicted renewable generation and market information |
| Yoo et al. (2014) [43] | Optimized Renewable and Sustainable Electricity Generation Systems for Ulleungdo Island in South Korea | PV-WT-Converter-Battery-DG-Hydro Turbine | The reduction of diesel fuel costs after introduction of hybrid energy system. |
| Mondal & Denich (2010) [44] | Assessment of renewable energy resources potential for electricity generation in Bangladesh | Grid-PV-WT-Biomass-Hydro | Potential of hybrid renewable energy system according to renewable sources. |
| Park et al. (2016) [45] | Economic and Environmental Benefits of Optimized Hybrid Renewable Energy Generation Systems at Jeju National University, South Korea | PV-WT-Battery-Converter | Potential configurations of renewable energy system for University. |

### 2.1. Population and Location

Gasado Island is one of the islands in Jindo, Jeollanamdo province, and is the first energy independent island in South Korea. The center of Gasado is 34°28′ N latitude and 126°2′ E longitude (Figure 1). The size of the island is approximately 160 households, 290 citizens, and an area of 5.56 km$^2$. The time zone is Greenwich Mean Time (GMT) +9:00, South Korea.




(**a**) (**b**)

**Figure 1.** A geographic maps of Gasado. (**a**). A box with a map of South Korea; (**b**). Enlarged map with coordinates of Gasado Island.

### 2.2. Energy Status and Policy

Gasado totally relied on internal combustion power generation, such as diesel generators, before the introduction of a micro-grid with hybrid energy, including wind turbines and PV. From October 2012 to September 2015, KEPCO and the Jeollanamdo provincial government worked on micro-grid projects in Gasado Island. They are currently using electricity produced by solar and wind power.

Before the micro-grid project of Gasado Island, other islands near Gasado Island installed small generators in every house. However, the construction of a power supply system is now proceeding in Gasado Island. The purpose of the construction is to send electricity (made of renewable energy in Gasado Island) to 10 nearby islands such as Anjwado.

## 3. Methods and System Configuration

HOMER is widely used to help with technological feasibility assessments and evaluating the profitability of a micro-grid consisting of a hybrid energy system from the point of view of a central or local government [8,46].

HOMER's simulation capability is summarized as, "it can simulate both grid-dependent and stand-alone electrification systems connecting loads, and comprises a hybrid system including PV panels, wind turbines, biomass power, reciprocating engine generators, small hydro, micro-turbines, fuel cells, batteries, and hydrogen storage." [47]. The NPC is the key economic factor of HOMER, as HOMER determines the ranking of all configurations according to the NPC after optimization and simulation [48].

### 3.1. Load Information

This study used the data from the "Gasado Real Daily Demand List", published by the KEPCO Research Institute, for the analysis. This study used the original electricity load profile without changing units or scaling the data set because Gasado is generally not consuming much electric energy. To use HOMER to simulate the hybrid system, 8760 hours of the real hourly load data set should be collected. Based on the seasonal load profile of Gasado Island, the daily profile, and the DMap (Figures 2–4), people consume a relatively enormous amount of power in August and during the evenings between 8 p.m. and 10 p.m. Figure 2 shows that the top of the blue box signifies the average daily maximum load, the black line in the middle of the blue box signifies the overall average load, and the bottom of the blue box signifies the average daily minimum load in Gasado.

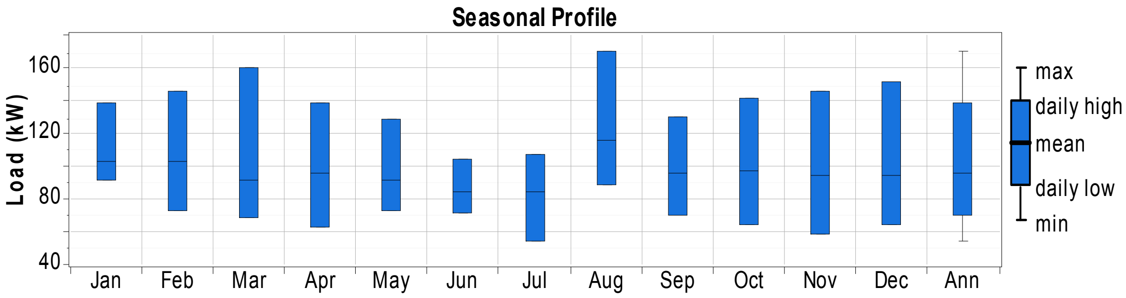



**Figure 2.** Seasonal profile for Gasado.

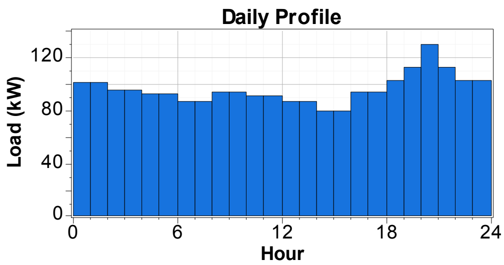



**Figure 3.** Average daily profile for Gasado.

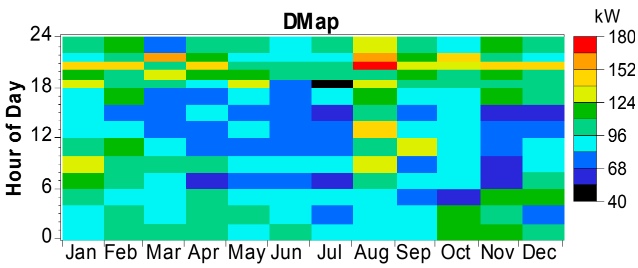



**Figure 4.** Monthly DMap for Gasado.

To simulate the system, which we want to simulate precisely, monthly average wind speed data and clearness indices are also required due to the renewable energy generation system, including wind turbines and PV, for this study.

### 3.2. Solar Energy Information

Solar energy is one of the most popular sources of electric power that is not exhaustible and carbon neutral [49]. This generation, however, entails considerable expense, especially for the initial installation. However, costs of solar energy for operation and management are much lower than other energy sources and can expand capacity easily according to the increase in the demand for energy. One of the most important advantages is that PV generates more power than usual when it is needed most, usually from 11 a.m. to 3 p.m.

The efficiency of PV panel power generation drops as time passes after installation, however, and is generally available up to 30 years. Solar power generation is derived from Equation (1) in HOMER

$$P_{PV} = Y_{PV} f_{PV} \left( \frac{\acute{G}_T}{G_{T,STC}} \right) \quad (1)$$

$Y_{PV}$ is the rated capacity of the photovoltaic panels (kW), $f_{PV}$ is the derating factor of the PV (%), $G_T$ is the radiation of the PV panels (kW/m$^2$), and $G_{T,STC}$ is the radiation of the PV panels in standard condition (kW/m$^2$). Solar irradiance and net present cost are negatively correlated, and their relation is quite linear.

Solar data collected by the Korea Meteorological Administration (KMA) in 2014 was used for the solar clearness and daily radiation indices inputs in the HOMER software. We compared the KMA data set to NASA data to use exact data and obtain a real solution. The data presented an average of 0.479 for the annual solar cleanness index and an average of 4.008 kWh/m$^2$/d for the daily radiation. Both values are higher than for the eastern coast of Korea. Moreover, the average solar radiation of Gasado Island is higher compared to the measured value for all of Korea. Figure 5 shows the horizontal radiation information of Gasado Island. A sensitivity analysis is performed with five different values near Gasado's rounded annual average daily radiation (kWh/m$^2$/d), which are 3.61, 3.81, 4.01, 4.21, and 4.41.

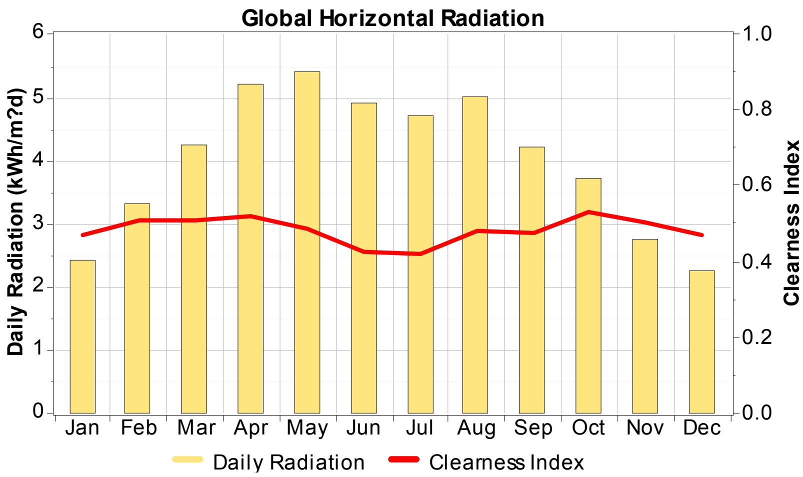



**Figure 5.** Average monthly solar radiation [kW/m$^2$/d] and clearness index of Gasado.

### 3.3. Wind Energy Information

Wind energy data collected in 2014 by both the KMA and NASA Surface Meteorology and Solar Energy based on Gasado Island's latitude and longitude were used [50]. Monthly average wind speeds (m/s) from January to December were 7.19, 7.32, 6.49, 5.99, 5.36, 5.10, 5.26, 5.39, 5.53, 5.87, 6.45, and 6.94, respectively. The data showed that the annual wind speed is 6.067 m/s. The monthly wind speed of Gasado Island is presented in Figure 6. This figure shows the tendency of Gasado Island to be windier compared to the rest of South Korea, so more power will be generated in Gasado Island than in other places in South Korea.

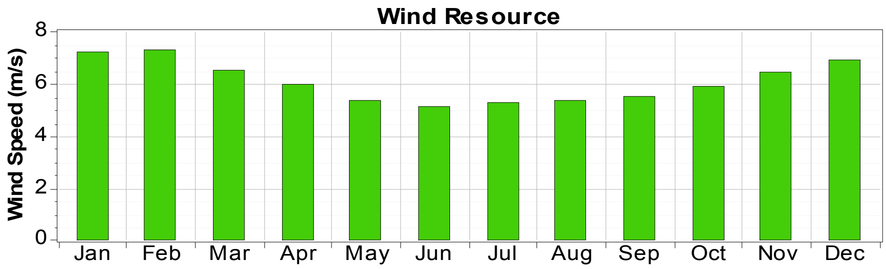



**Figure 6.** Average monthly wind speed [m/s] profile of Gasado.

Sensitivity analysis is done with five values near Gasado Island's wind speed mean, which are 5.07, 5.57, 6.07, 6.57, and 7.07 m/s. In addition, the anemometer height, the Weibull coefficient, the one hour autocorrelation factor, the diurnal pattern strength, and the hour of peak wind speed were assumed as 10 m, 2, 0.85, 0.25, and 15, respectively. These are default values in HOMER. Given this weather information, Gasado Island has relatively stronger wind power than the average city or island in the eastern coast of South Korea. Wind power generator output is derived from Equation (2) in HOMER.

$$P_m = \frac{1}{2} \times \rho \times A \times v^3 \times C_p \quad (2)$$

There are four main coefficients used to calculate the output: v denotes the wind velocity (m/s), $\rho$ is the air density (kg/m$^3$), A is the rotation surface of the rotor (m$^2$), and $C_p$ is the output factor of the wind turbine. The type of wind power generator used in this study is the BWC Excel-S manufactured by Bergey Windpower (Norman, OK, USA), which provides 10 kW of AC-rated power (Figure 7).

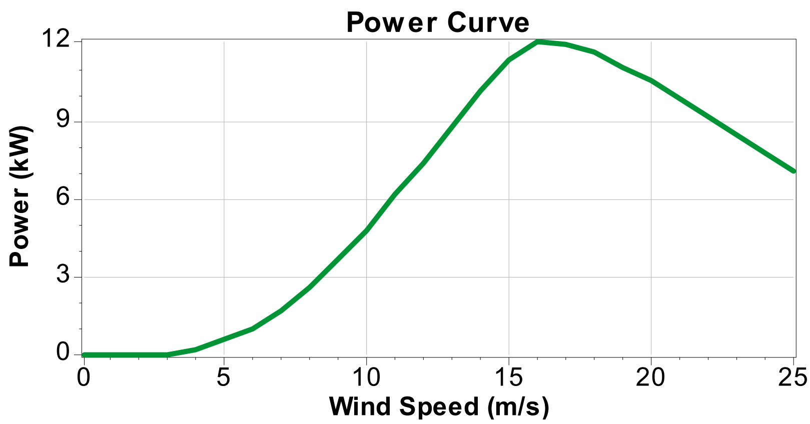



**Figure 7.** Power curve of wind turbine.

### *3.4. Diesel Fuel Price*

This paper performed a sensitivity analysis on the price of diesel fuel and decided the average diesel price to be $1.8 per liter due to the posted price in South Korea [51,52]. In this study, diesel levels show a lower heating value of 43.2 MJ/kg, a density level of 820 kg/m$^3$, a carbon content level of 88%, and a sulfur content level of 0.33%.

### *3.5. Economic Variables*

There are several important economic variables to be calculated in the simulation, such as the project period and real interest rate. Most renewable energy generation needs a long time frame to complete the project. In previous studies, the duration of the project was assumed to be 20 or 30 years. This study also assumed that the project duration would be 20 years. This study uses an annual real interest rate of 3.91%, as referenced from recent literature on an economic analysis of hybrid energy in South Korea [52].

### *3.6. Photovoltaic Panels*

In this study, the initial installation costs of solar panels, replacement costs, and annual operating and maintenance (O&M) costs per 1 kW capacity were assumed as $1800, $1800, and $25, respectively. This value, which previous studies used, was based on the IPCC and a declared price of several Korean companies [11]. Some previous studies assumed that the annual maintenance cost of PV would be $0 [53].

The lifetime of panels was assumed to be 20 years. A derating factor of 0.8 was assumed. The derating factor of 0.8 means that the productivity of the panel will be reduced by 20% due to the changing effects of the external factors on the panels. This study also considered the effects of temperature (i.e., a temperature coefficient of power of −0.5%/°C, a nominal operating cell temperature of 47 °C, and an efficiency level at the standard test conditions of 13%). This study assumed that all panels have a fixed angle of inclination. A reflectance of 20% was assumed, and a sensitivity analysis of the PV panel was considered for a range from 0 to 600 kW.

### *3.7. Wind Turbines*

In this study, the BWC Excel-S 10 kW AC was used, which was also mostly used in previous studies [11,43]. It was also applied to Gasado Island in practice. The initial installation costs, replacement costs, and annual operating and maintenance costs of a turbine were assumed to be $29,000, $25,000, and $400, respectively. The turbine's lifetime and the height of the hub were assumed to be 25 years and 25 m, respectively. A sensitivity analysis of the wind turbines was considered for a range from 0 to 120 units.

### *3.8. Converters*

The converters are used to make the electric energy flow between AC and DC [31]. This study assumed the initial installation costs, replacement costs, and annual O&M costs would be $80,000, $75,000, and $2000 per 100 kW size, respectively [36]. The lifetime of the converter was assumed to be 15 years and the efficiency to be 90%. The capacity of the rectifier was equivalent to the capacity of the inverter, and the efficiency was assumed to be 85%. A sensitivity analysis of the converters was considered from 0 to 300 kW.

### *3.9. Generators*

In much research on hybrid energy systems, generators powered by conventional fuels usually complement the intermittently generated renewable energy. Of course, a generator is necessary in energy independent islands such as Gasado Island. This study assumed that the initial installation costs, replacement costs, and annual O&M costs would be $450, $450, and $0.20, respectively, per 1 kW size.

According to previous studies, many papers assumed that the cost for using fuel tanks would not occur [37]. A lifetime of 15,000 operating hours was used in the simulation with a minimum load ratio of 30%. In addition, this study assumed that the fuel curve has an intercept coefficient of 0.08 L/h/kW rated and a slope of 0.25 L/h/kW output as given values. A sensitivity analysis of the generators was considered from 0 to 250 kW.

### *3.10. Batteries*

The hybrid system we suggested should have a battery as a complementary device because the renewable energy we use generates electricity intermittently due to the irregularity of the energy sources. Many previous studies about hybrid systems assumed that the characteristics of the battery remain constant within its lifetime and are not directly affected by external environment variables such as humidity and temperature [46]. An energy storage system is too expensive to make hybrid systems economically feasible. However, an energy storage system is necessary to reduce the fluctuation of both the load and electrical power generation, improve the efficiency of operation of the hybrid system, and provide security for the energy supply [37].

In this study, the Surrette 6CS25P battery (Rolls/Surrette, Springhill, NS, Canada) was used, which was selected in most papers about renewable energy generation systems, in order to investigate the optimal hybrid system [31,37,53]. The initial installation cost of the battery, replacement cost, and annual maintenance cost were assumed to be $1229, $1229, and $10 per battery, respectively.

A sensitivity analysis of the battery was considered for a range from 0 to 2500 units. The initial state of the battery is assumed to be fully charged.

### *3.11. Government Plan in Gasado*

The hybrid system that was installed in Gasado Island by KEPCO includes converters, batteries, diesel generators, PV arrays, and wind turbines. Specifications of each device are shown in the table below (Table 2).

**Table 2.** Device specifications of the hybrid system in Gasado Island.

| Type | Standard | Specification |
|---|---|---|
| Operating System | SCADA + EMS Application | Forecast, SOC management |
| Converter | 500 kVA × 2, 250 kVA × 1 | Grid Forming, PQ Operation |
| Battery | 3 MWh | Lithium ion, 1C-rate |
| Wind Turbine | 100 kW × 4, PMSG | Output limitation, LVRT |
| PV | 314 kW | Output limitation, Photovoltaic on water |
| Diesel Generator | 100 kW × 3 | Droop operation |
| Demand Management | Water supply, Air conditioner | Renewable surplus output control |

When simulating the system to investigate feasibility, each device was set up to include the replacement cost that will be needed after the lifetime of each facility, the annual operation with its associated maintenance cost, and the initial installation cost. For a more accurate comparison, we used the same values as those described above for the optimal solution (as shown in Table 3).

**Table 3.** Costs of generator type for Gasado Island.

| Generator Type | Capital | Replacement | Annual O&M Cost |
|---|---|---|---|
| Wind Turbine (BWC Excel-S) | 29,000 | 25,000 | 400 |
| PV (1 kW) | 1800 | 1800 | 25 |
| Battery (Surrette 6CS25P) | 1229 | 1229 | 10 |
| Diesel (1 kW) | 450 | 450 | 0.2 |
| Converter (1 kW) | 800 | 750 | 20 |

This study compared and analyzed the case that KEPCO built in practice and the optimal case that we suggest. In this study, hybrid systems, which combined conventional diesel generators and renewable energy generation, would be analyzed based on both NPC and COE to investigate the economic and technological feasibility. When using HOMER to optimize the hybrid systems, the most important economic factor is the NPC. Economic factors and system configurations were analyzed without weighted sensitivity analyses. In this study, 75 sensitivity analyses and 40,320 simulations were carried out. A total of 3,024,000 combinations were simulated to determine the optimized solution for Gasado Island.

## 4. Discussion

This study compared the Korean government plan (KEPCO) to the optimal hybrid system that HOMER suggested.

### *4.1. Korean Government Plan*

In the simulation result of the hybrid system that KEPCO built, 28% of electric power is expected to be produced from the PV arrays, 59% from wind turbines, and 13% from diesel generators (Figure 8). Therefore, the renewable fraction is 0.87. Based on the monthly electricity production, we determined that almost all of the electric power is generated by renewable energy. The underlying power generation is from wind turbines and the production of electricity from solar panels.

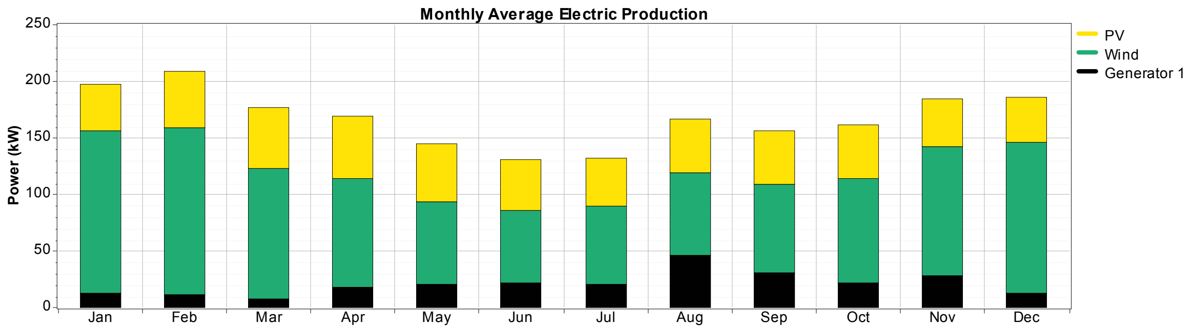



**Figure 8.** Monthly average electric production of the government plan.

This study found that the government's micro-grid plan is less economically feasible than a grid-dependent (on-grid) system if this system is located within 291 km of the grid (Figure 9). However, recent energy policy trends of independence and renewable energy utilization do not aim simply for economic feasibility. Because a major policy is usually related to long-term goals, such as global environmental issues and sustainable development, we cannot treat the validity of the business model only by the distance to the grid.

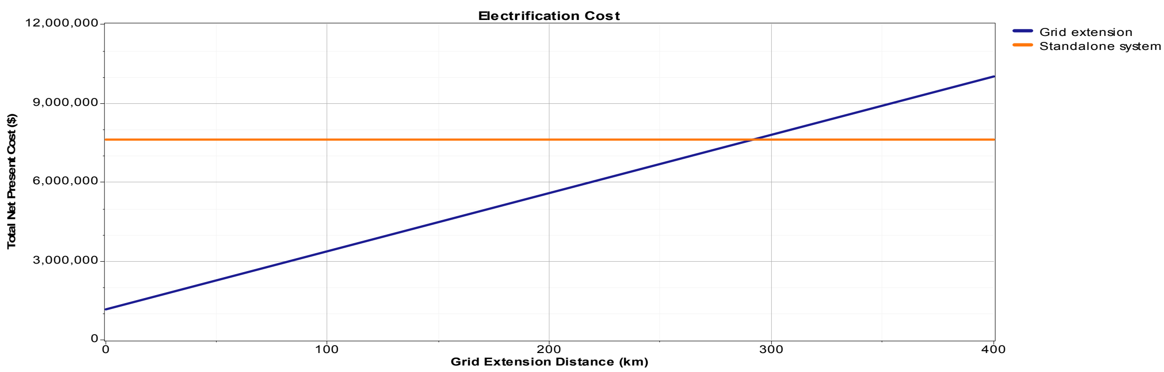



**Figure 9.** Electrification cost for the government plan by grid extension distance.

Gasado Island generates electric power using a hybrid system, including renewable energy sources and diesel generators; they produce greenhouse gas emissions as shown in Table 4. Though the carbon emission trade is not yet active in South Korea, if it is vitalized successfully, this system will become more economically feasible. In addition, if, in the near future, the 62 islands are developed by private-sector investment projects, such as Build-Transfer-Lease (BTL) projects, then public operators can be expected to leverage the carbon trading system.

**Table 4.** Amounts of greenhouse gas emissions for the government plan.

| Pollutant | Emissions (kg/Year) |
|---|---|
| Carbon dioxide | 203,909 |
| Carbon monoxide | 503 |
| Unburned hydrocarbons | 55.8 |
| Particulate matter | 37.9 |
| Sulfur dioxide | 409 |
| Nitrogen oxide | 4491 |

Cash flow summaries are shown in Figure 10 and Table 5.

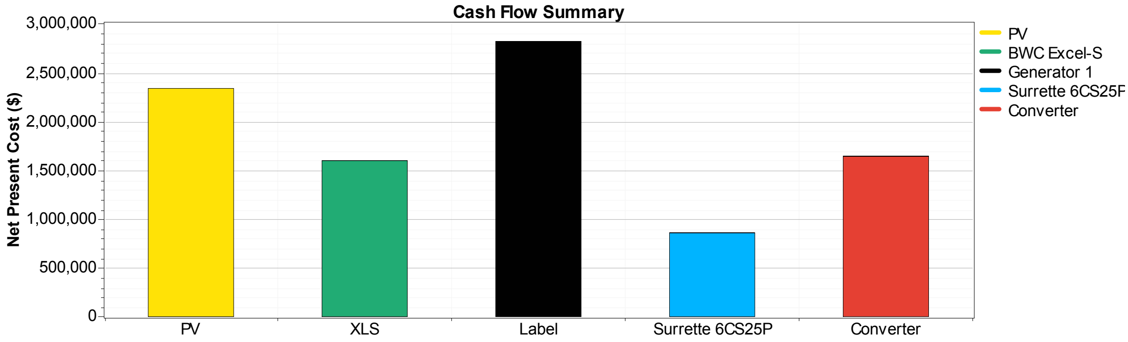



**Figure 10.** Cash flow of government plan by component.

**Table 5.** Simulation results for a government plan.

| Component | Capital ($) | Replacement ($) | O&M ($) | Fuel ($) | Salvage ($) | Total ($) |
|---|---|---|---|---|---|---|
| PV | 565,200 | 0 | 107,539 | 0 | 0 | 672,739 |
| BWC Excel-S | 1,160,000 | 0 | 219,188 | 0 | −92,872 | 1,286,317 |
| Diesel Generator | 135,000 | 86,811 | 1,071,009 | 1,909,420 | −16,466 | 3,185,774 |
| Surrette 6CS25P | 553,050 | 349,041 | 61,647 | 0 | −85,604 | 878,133 |
| Converter | 1,000,000 | 527,364 | 342,482 | 0 | −290,224 | 1,579,623 |
| Total System | 3,413,250 | 963,216 | 1,801,866 | 1,909,420 | −485,166 | 7,602,586 |

### *4.2. Optimal Solution from HOMER Simulation*

With the HOMER solution, it was found that the combination shown in Table 6 is the most economically feasible.

**Table 6.** Optimal hybrid energy combination for Gasado (compared with the government plan).

| Type | Optimal Solution | Government |
|---|---|---|
| Converter | 200 kVA | 1250 kVA |
| Battery | 5.2 MWh | 3 MWh |
| Wind Turbine | 400 kW | 400 kW |
| PV | 400 kW | 314 kW |
| Diesel Generator | 100 kW | 300 kW |

In this system, wind energy is the primary source of the underlying electric power. PV panels also generate substantial electricity. A total of 36% of electric power is generated by PV panels, 61% from the wind turbines, and 3% from the diesel generators (Figure 11). The fraction of renewable energy from the optimal solution is greater than that of the government plan (0.97 > 0.87). The optimal system is less dependent on the use of diesel than the government plan. We determined that our simulation system takes advantage of more batteries.

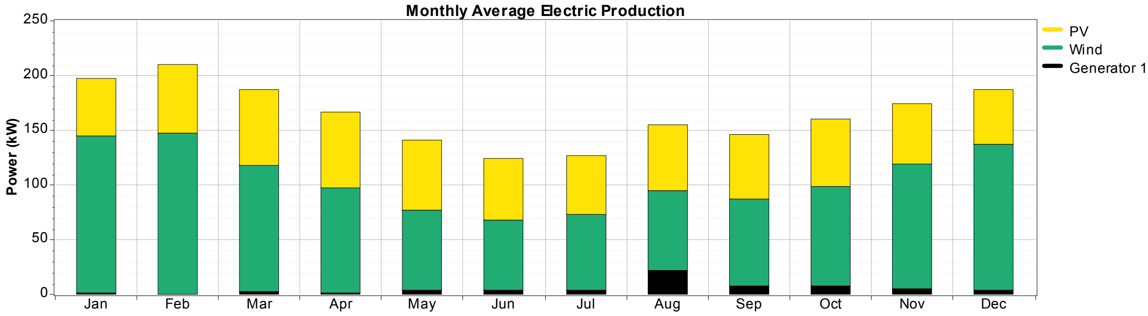



**Figure 11.** Monthly average electric production of the optimal solution.

The optimal system was more economically feasible than a grid-connected system if this system is located beyond 149 km from the central electrification line (Figure 12). Given both distances that guarantee economic feasibility, it is easier for the optimal system to build an energy independent system compared to the government plan (149 km < 291 km).

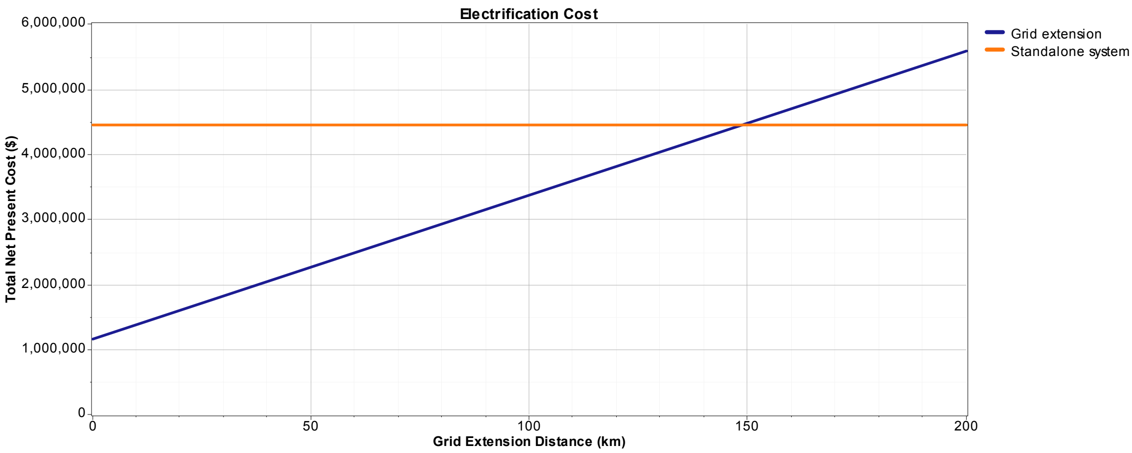



**Figure 12.** Electrification cost for the optimal solution by grid extension distance.

If the optimal system is built, it will produce greenhouse gas emissions as shown in Table 7. These levels are much less lower than the micro-grid system built by the government.

**Table 7.** Amounts of the greenhouse gas emissions for the optimal solution.

| Pollutant | Emissions(kg/Year) |
|---|---|
| Carbon dioxide | 42,399 |
| Carbon monoxide | 105 |
| Unburned hydrocarbons | 11.6 |
| Particulate matter | 7.89 |
| Sulfur dioxide | 85.1 |
| Nitrogen oxide | 934 |

Cash flow summaries are shown in Figure 13 and Table 8.

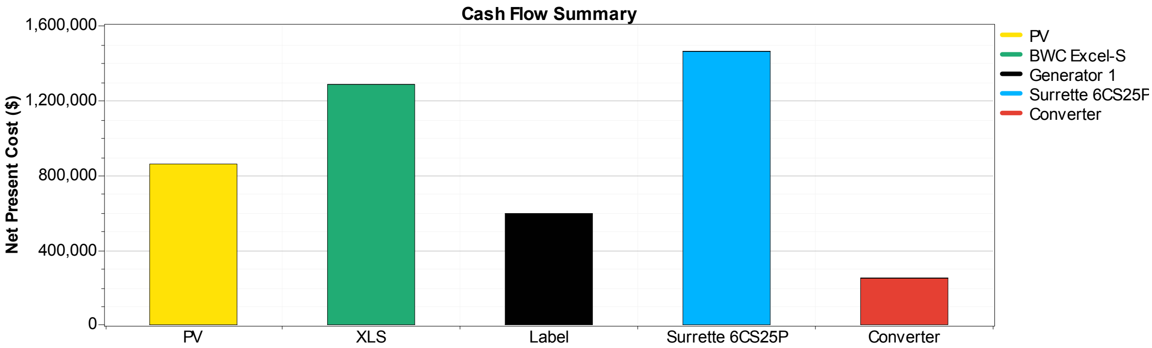



**Figure 13.** Cash flow of optimal solution by component.

**Table 8.** Simulation results for the optimal solution.

| Component | Capital ($) | Replacement ($) | O&M ($) | Fuel ($) | Salvage ($) | Total ($) |
|---|---|---|---|---|---|---|
| PV | 720,000 | 0 | 136,993 | 0 | 0 | 856,993 |
| BWC Excel-S | 1,160,000 | 0 | 219,188 | 0 | −92,872 | 1,286,317 |
| Generator 1 | 45,000 | 0 | 161,377 | 397,025 | −4486 | 598,917 |
| Surrette 6CS25P | 921,750 | 581,734 | 102,745 | 0 | −142,674 | 1,463,555 |
| Converter | 160,000 | 84,378 | 54,797 | 0 | −46,436 | 252,740 |
| System | 3,006,750 | 666,113 | 675,100 | 397,025 | −286,467 | 4,458,522 |

### 4.3. Interpretation and Implication

The hybrid system was built based on the government's plan in Gasado Island by KEPCO. The total amount of the electric power load was determined with consideration for South Korea's electric utility industrial law, such as multiplying the number of households by 3 kW and the number of stores by 5 kW. They also considered the amount of electricity other facilities will use. They considered that PV panels can produce electric power 3 hours and 30 minutes a day based on the three-hourly solar radiation data sets that the KMA provides.

In this study, the results compared the government's plan and the optimal hybrid system, which we suggest have substantial differences in their NPC, as shown in Table 9. If the government built a hybrid energy system as we suggested, it would be less costly and provide a higher fraction of renewable energy. They could use more PV and batteries and fewer diesel generators and converters.

**Table 9.** Comparison of optimal solution and government plan.

| System | PV (kW) | Wind Turbine (kW) | Diesel Gen. (kW) | Battery (unit) | Converter (kVA) | Total NPC ($) | Renewable Fraction (%) |
|---|---|---|---|---|---|---|---|
| Optimal Solution | 400 | 400 | 100 | 750 | 200 | 4,458,523 | 0.97 |
| Government Plan | 314 | 400 | 300 | 450 | 1250 | 7,602,588 | 0.87 |

A power supply system that is mainly dependent on renewable energy sources that generate electricity intermittently under different weather conditions should have an energy storage system, such as batteries, to prevent blackout incidents because the system should be prevented from fluctuating and breaking down. Therefore, the price competitiveness of the energy storage system is necessary to expand the supply of renewable energy. The current price of energy storage systems is about one-third of the price five years ago. If the battery industry continues to develop at the same level as the present for a few more years, then our optimal solution is expected to fully achieve economic feasibility.

## 5. Conclusions

In the hybrid system, as dependence on renewable energy power generation increases, both the operating time of the conventional generator and the consumption of diesel will be reduced. HOMER determines the time that generators should be run per year, and then calculates the operating and maintenance cost, including diesel prices, based on its own algorithm. However, the government should no longer depend on the diesel generators, using one of the conventional energy sources.

As an alternative to centralized grid systems, hybrid systems and micro-grids should be re-evaluated. In addition, the government should determine which hybrid system is the most technologically, economically and environmentally feasible solution to supply stable electric power to the island without the grid. The hybrid system can have diverse combinations, including PV panels, wind turbines, fuel cells, and batteries as one of the energy storage systems, hydrogen storage systems, electrolyzers, and diesel generators.

The hybrid energy micro-grid built by KEPCO has been evaluated successfully. It showed that the hybrid system is economically acceptable and stable enough to supply electric power to the island. Not only has KEPCO built a stable power supply system, but it has also developed an optimal energy management system (EMS), which is capable of predicting the overall power generation and load of the island, managing the charge and discharge of the batteries, and automatically controlling the distributed power source [54]. However, this paper is significant because it shows that KEPCO was able to cut costs and augment the fraction of renewable energy. Based on the optimization results, this paper offers strategies to the South Korean government for establishing new energy policies and guidelines. The government intends to drastically reduce power supply costs and $CO_2$ emissions by minimizing the use of existing diesel generators and expanding the construction of 'Green Energy Independent Islands' in 120 island areas based on the Gasado Island micro-grid model. In addition, the government is planning to collaborate with domestic companies to actively advance into the rapidly growing overseas micro-grid market, and they will further enhance the reliability of domestic micro-grid systems. These research results are expected to be helpful for not only the South Korean government but also for other countries.

This paper used HOMER for computer simulations. HOMER models simulate all the hybrid systems at an hourly interval. Therefore, HOMER determines useful research results by estimating performance and feasibility. The sensitivity analysis was conducted considering the change in future diesel prices, several economic factors, average electricity consumption, which is expected to increase, and indices related to the weather. This program, however, does not show the results within an hour. In other words, when simulating PV and solar thermal energy, HOMER is stable. However, when simulating wind energy, HOMER has a bit of uncertainty during the optimization process due to modeling power generation systems by the hour. In addition, HOMER does not consider the effort and preparation of members living in the area and determines the optimal hybrid system based on the total load data for the previous year. The final weak point of HOMER is that it cannot separate between essential and non-essential loads.

The most advanced energy solution necessary for developing countries, based on renewable energy sources, could guarantee the supply of reliable energy to islands that are unexposed districts with no access to electricity. This study is one of the most successful examples of an optimal hybrid system that includes renewable energy. In the near future, it will be necessary to study the movements of the population, power consumption, and the decentralization of electric power to determine an optimized solution for renewable energy. In addition, although power generation is also important, saving energy and efficient uses on the load side will be vitally important to analyze.

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## Abbreviations

| | |
|---|---|
| HOMER | Hybrid Optimization Model for Electric Renewables; |
| NREL | National Renewable Energy Laboratory; |
| KEPCO | Korea Electric Power Corporation; |
| PV | Photovoltaic; |
| NPC | Net Present Cost; |
| COE | Cost of Energy; |
| GHG | Green House Gas; |
| DG | Diesel Generator; |
| WT | Wind Turbine; |
| FC | Fuel Cell; |
| GMT | Greenwich Mean Time; |
| XLS | BWC Excel-S; |
| Label | Diesel Generator; |
| EMS | Energy Management System; |
| KMA | Korea Meteorological Administration. |

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