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Article

Optimal Hybrid Renewable Power System for an Emerging Island of South Korea: The Case of Yeongjong Island

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Abstract: South Korea, which has led in “green growth” since 2012, is now focusing on investigating new-growth engine industries such as the gaming industry and mega-resort development. Yeongjong Island is the most representative and promising location for nurturing the gaming industry, which has already generated more than 20 billion USD. However, the construction of mega resort clusters generates critical energy issues. Despite this potential problem, local governments and South Korea’s central government have not yet established a sustainable energy blueprint plan. Thus, we analyzed and suggested an optimal hybrid renewable power system for Yeongjong Island by using empirical data (load data, climate data, equipment data, and economic variables). The results of the study academically show 100% of electricity in Yeongjong Island with renewable energy-oriented hybrid system technologically, economically, and socially feasible for the following reasons: First, the island’s renewable energy station has a lower cost and a shorter construction period than other energy stations. Second, the island’s renewable energy station produces no carbon dioxide and has no risk of other environmental pollution that may encounter resistance from local residents.

Keywords: HOMER; sustainability; renewable energy; microgrid

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1. Introduction

Sustainability has become a crucial global issue for both industrial growth and public development because of rapid population growth and CO_2 emissions [1,2]. Therefore, the majority of governments have enacted policies and specific programs (e.g., FIT; feed-in-tariffs, quota obligation, subsidy, and tax incentives) to promote the use of renewable energy [3–7]. East Asian countries have begun to concentrate more on sustainable development after experiencing several energy crises (e.g., the global oil crisis and the Fukushima accident). China, the largest greenhouse gas (GHG) emission nation, is confronted with the pressures of high energy demand and dependency on fossil fuel, which have led to the exploration of green growth [8–11]. Japan has also reformed its energy mix from a fossil-fuel dependent structure to a renewable and clean energy-driven structure after experiencing fatal accidents in Fukushima [12]. South Korea, as a rapidly industrialized country that lacks natural resources, has long attempted to increase energy independency by expending renewable energy [13]. The Korean government planned to reduce the quantity of GHG emissions by 70% over 12 years [14–18].

The Korean government has attempted to find a new growth engine industry that possesses sustainable capacity to enable development with less pollution and resource consumption in contrast to traditional manufacturing. One representative project is the construct of the mega leisure resort in Yeongjong Island near Seoul. As of June 2015, more than 10 multinational corporations have participated in the resort project, and more than 20 billion USD has been invested in this island. Compared with other cases that have experienced spectacular economic growth through a casino boom, the construction of mega resorts generates many critical issues, including an energy shortage problem [9,19]. For example, the fast pace of Macao's economic growth resulted in a rapid increase in energy use and GHG emissions [10], and local residents have suffered from its energy inefficiency. Singapore has adopted energy strategies such as a lower dependency on coal, the liberalization of its power sector market, and an increase in the use of a renewable energy system for its sustainable energy supply [20]. For Yeongjon Island, which has the largest international airport in the world, there is a greater possibility of a more serious electricity shortage problem than for any other mega resort. The government cannot build a nuclear plant or water dam in a short period, and two of the nearest metropolitan cities, Incheon and Seoul, encounter serious black-out problems every summer [21]. Thus, the introduction of renewable energy and the creation of a hybrid energy source system are the most effective and sustainable means to increase the energy resilience of Yeongjong Island.

Although the South Korean government has recently executed a renewable energy action plan [14,22], minimal research has examined the feasibility of a hybrid system of renewable energy that can be applied to practical circumstances and can provide significant implications using empirical data. Many researchers are still interested in issues regarding the feasibility and reliability of a hybrid energy system including renewable power sources in the suburbs. Because we can totally depend on the conservative types of power generation no more, such as nuclear or thermoelectric power. This study academically investigates which hybrid energy system could be the most economically feasible for the electric power supply of Yeongjong Island using computer simulation. To fill this gap, this study's objective is to investigate an optimized renewable power generation system for the emerging island of South Korea, Yeongjong Island, by using its electricity consumption data, climate data, and economic variables.

2. Overview of Hybrid Renewable Power System and Yeongjong Island of South Korea

2.1. Hybrid Renewable Power System

Many concerns about energy management such as lack of fossil fuels are reported steadily. Thus, hybrid energy systems which include renewable energy sources are increasingly studied and developed for both grid-dependent and stand-alone systems. However, even if hybrid energy systems are very trendy and attractive, they generate electric power intermittently and require the use of expensive energy storage systems (ESS). The systems usually include different kinds of energy generators to gain as much advantages as possible from each energy source [23,24].

Thus, researchers who studied hybrid renewable power systems have mostly focused on specific objects, including schools, buildings, cities, and islands because the characteristics of renewable energy are mostly suitable for places in need of energy independence [25–29]. Especially, among these research objects, islands have become the most valuable research areas because islands are geographically isolated and need more expensive grid connection fee than other objects [30–34].

There are also many studies on hybrid renewable power systems for Asian islands, including South Korea [35–41]. For example, many researchers have studied Jeju Island, Ulleung-do, Geoje-do, Jin-do, and Wan-do [14,42]. Jeju Island, which is the largest island in South Korea, is not only far from the Korean peninsula but is also not connected to the mainland. Due to several blackout accidents in South Korea, Jeju Island should be a stand-alone island that promotes sustainable and stable electrification. Ulleung-do requires an independent power generation system because of both its large scale and its distance to the main land. Geoje-do has grown based on heavy industry, which relies heavily on energy. These islands in South Korea have reasons for attempting to introduce a hybrid renewable power systems.

Yeongjong Island, which is the object of this research, is different from the islands discussed above. This island is very close to Seoul, the capital of South Korea, and is connected to Seoul by two bridges that facilitate the development of land transportation, such as a highway and express railway. Incheon international airport is on Yeongjong Island, and the Newtown and mega projects are under construction. Research is needed to understand the advantages and disadvantages of the characteristics of the city and the island to craft an effective policy and plan.

2.2. Profile of Yeongjong Island

As shown in the Figure 1, Yeongjong Island, which has approximately 59,542 residents, is located approximately 30 km west of Seoul at 37.4958660 north latitude and 126.5307310 east longitude. The island is approximately 63.81 km^2 and is the fifth largest in South Korea. Because Incheon International Airport on Yeongjong Island has been named the “World’s Number 1 Airport” for 10 consecutive years, this island has become known as the Asian logistics center. It was also designated an Incheon Free Economic Zone (IFEZ) with Cheongra and Songdo. Therefore, the island can attract considerable foreign investment. Over the past five years, 95% of the foreign direct investment attracted to South Korea's free economic zones occurred in the IFEZ. Furthermore, Yeongjong Island is within two hours of Beijing, Shanghai, Tokyo, Osaka, and more than 10 mega cities by airplane and 4 h from Hong Kong, Taipei, and Macau by airplane. These areas represent more than one billion people.

The expectation that the energy demand of Yeongjong Island, which was developed by the South Korean government, will rapidly increase according to the pace of development is a serious problem. Currently, most of the power used on Yeongjong Island is generated and supplied by the main grid. Using electricity through the main grid is contrary to sustainable and green development. The island is already suffering from a lack of energy because of the building of large theme parks, such as casinos. Approval of the development of Newtown in Yeongjong Island has been delayed because of the lack of a stable power supply. However, Yeongjong Island cannot have hydroelectric power plants because of its geographical conditions. Ganghwa-Ongjin-Yeongjong tidal power station, which was to be completed by 2012, has not been built because of the enormous cost of the initial construction and operation/management for power plants. Because people have lived through the failure of past mega projects, such as the four-river refurbishment project, the eco-system destruction, and because of the major impacts on residents' quality of life, people have strongly opposed the construction of additional power plants. Furthermore, a connection to Sihwa tidal power plants and to biomass power plants in Cheongna landfill necessitate enormous cable construction costs.

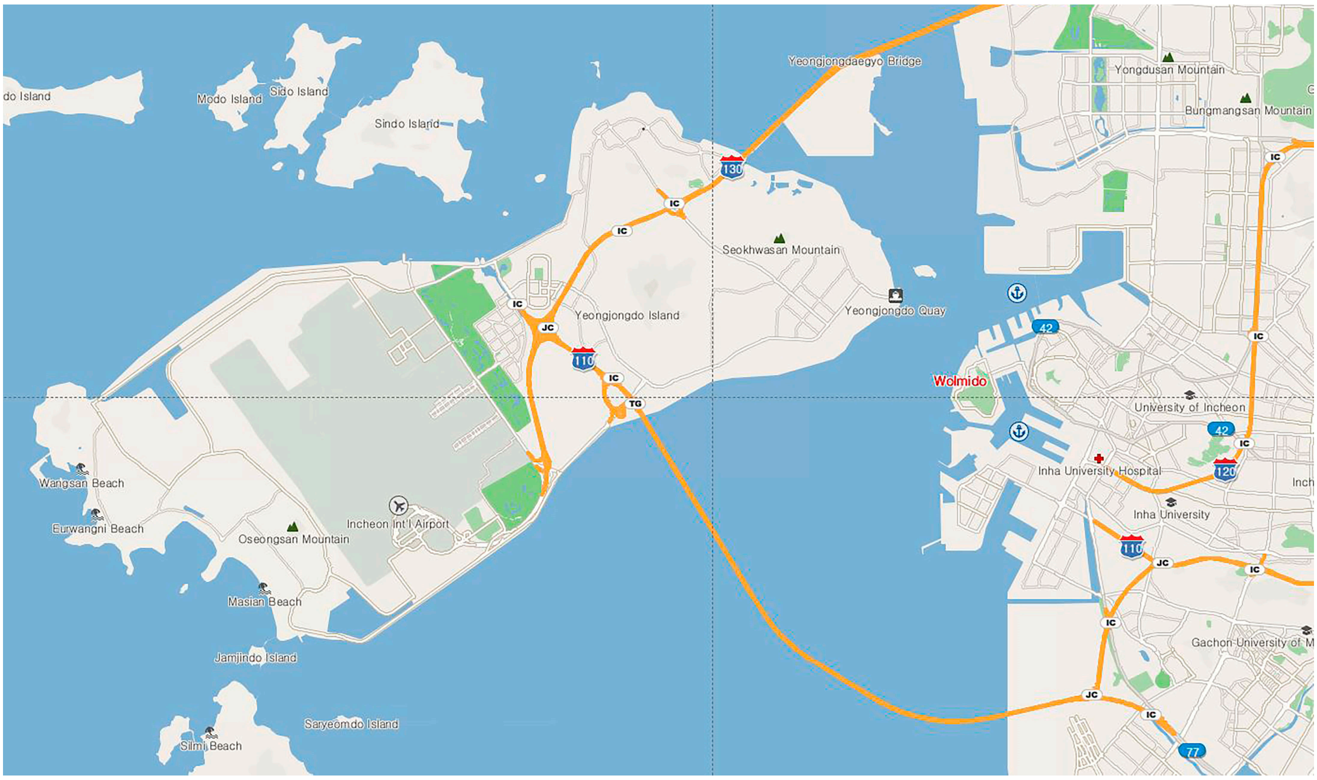

Figure 1. Geographical map of Yeongjong Island.

2.3. Energy Status and Policy of Yeongjong Island

Most electric power used on Yeongjong Island is supplied by a cogeneration plant and other types of plants in the Seoul-Incheon area. The renewable energy plan for this island, which is governed by Incheon city, Incheon international airport corporation, the IFEZ, and the Korean government, is in the conceptual stage or has had no progress because of difficulties such as enormous initial investment costs.

To prepare for a severe power shortage problem, it is necessary to pursue the diversification of energy sources with high development potential, such as renewable energy. In this study, we use an empirical data and analysis program named HOMER to propose an optimized hybrid energy generation system for the Yeongjong Island area.

Because Incheon Airport Energy, which supplies district heating (the community energy system), has financial problems, it cannot promote a second-stage heating supply business that costs approximately 130 million USD. Consequently, the district heating supply in Yeongjong Island is lacking, and there is a large problem with the additional supply to apartments. Therefore, the company plans to introduce a "Green Home Project" for apartments to achieve high energy efficiency and energy self-sufficiency as a means of promoting the harnessing of renewable energy. Green building certification based on energy economy is also used.

3. Method

3.1. Load Profile

We used the data called "Yeongjong Island Real Daily Demand List," issued in 2014 by the Korea Electric Power Coporation. We used 24 hourly load values for 365 days for an accurate analysis. The method we used in this study required data for each of the 8760 h in a year for the electrical load as well as the resource being harnessed, in this case, solar and wind power. The power supply of Yeongjong Island is relatively low from May to September compared with other periods because of the weather conditions during this period. As shown in the Figure 2, the power consumption is low from May to July. The power consumption pattern is quite similar to this except for several months.

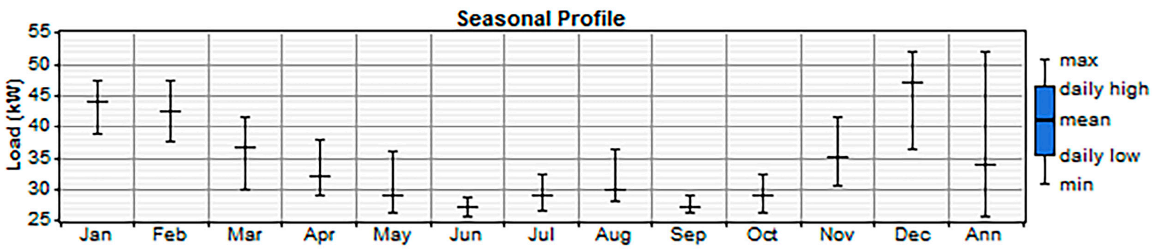

Figure 2. Seasonal load profile of Yeongjong Island.

Additionally, we analyzed the total load in kWh instead of MWh to ensure the preciseness and straightforwardness of the simulation [14,42].

3.2. Climate Data

3.2.1. Solar Energy Resources

Solar energy, which generating electricity through a photoelectron effect with no pollution, is the main focus of renewable energy [2]. Although solar energy has enormous potential, a solar energy-driven system remains an expensive option. PV systems produce electricity during periods when demand reaches a maximum on sunny days according to peak electricity consuming periods.

We obtained solar energy resource data from "NASA Surface Meteorology and Solar Energy" [43] that are based on geographic information of Yeongjong Island (Latitude: 37°29′, Longitude: 126°31′). In addition, the time zone was set at GMT+9:00, which includes Japan, North Korea, and South Korea. The average annual solar clearness is 0.501, and the average daily radiation is 4.049 kWh/m^2/d. These are suitable linear correlations between the solar irradiation and NPC. Figure 3 shows the monthly solar energy production of Yeongjong Island.

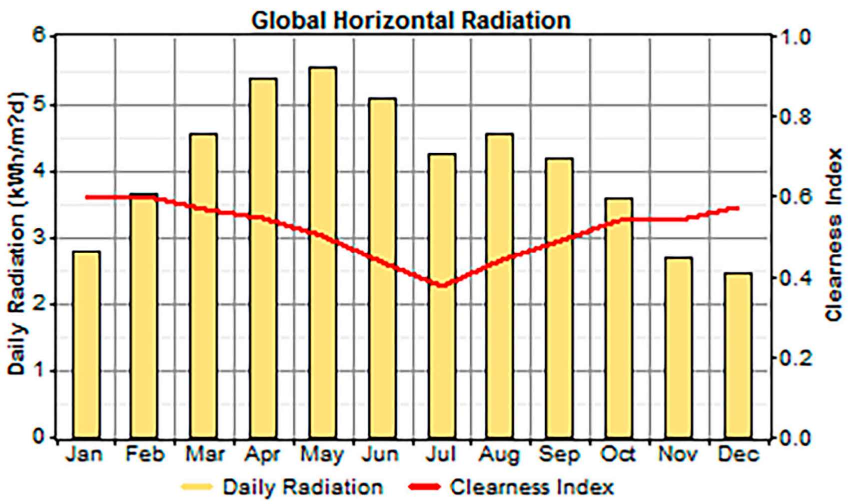

Figure 3. Monthly solar resource.

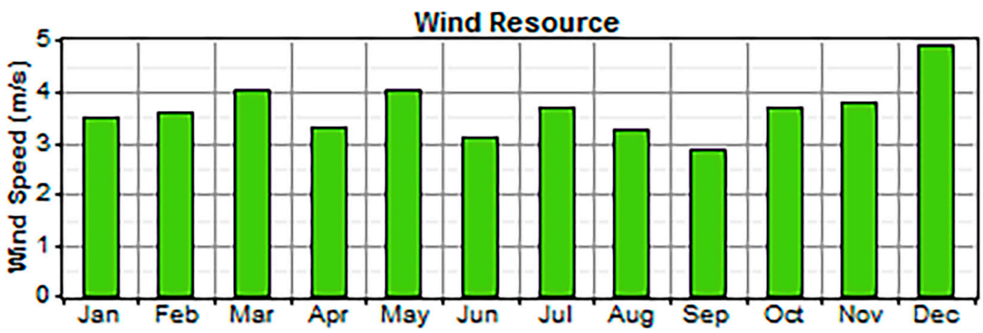

Figure 4. Monthly wind resource.

3.2.2. Wind Energy Resources

We obtained wind energy resource data from both the Korea Meteorological Administration (KMA) and the Korea Aviation Meteorological Agency (KAMA). According to the KMA and KAMA [44], annual average wind speed of Yeongjong Island's is 3.65 m/s at 6.9 m of altitude and 10 m of anemometer height. Figure 4 shows the monthly average wind speed of Yeongjong Island, and Figures 5 and 6 shows the annual wind direction of Korean peninsula. Additional data was provided by HOMER and the values used by previous research [14,42].

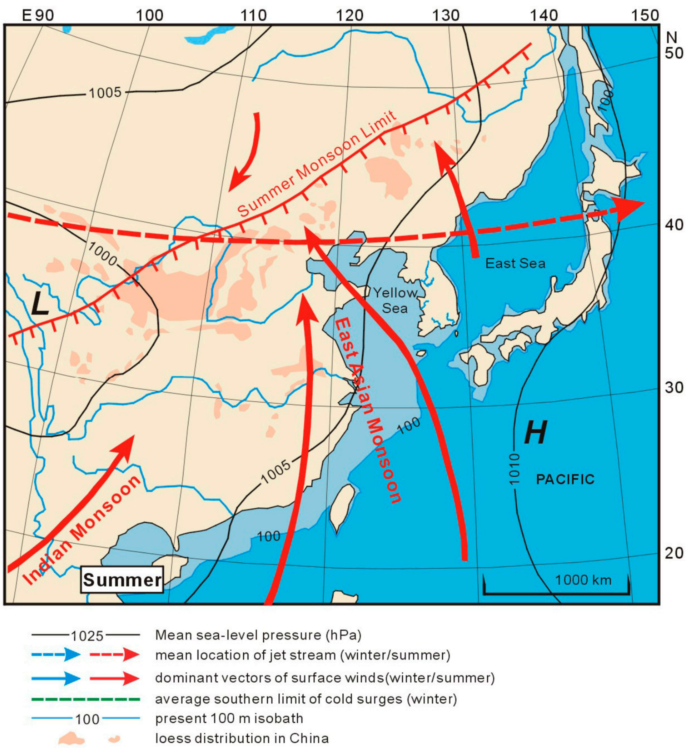

Figure 5. Annual wind direction of Korean peninsula (summer).

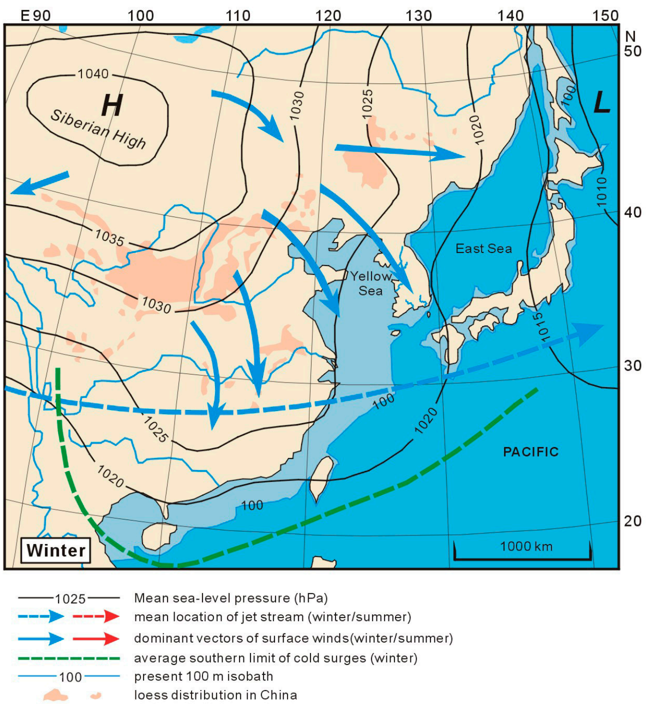

Figure 6. Annual wind direction of Korean peninsula (winter).

3.3. Economic Data

3.3.1. Interest Rate

Our study uses the annual real interest rate for greater accuracy [14,42]. The 2015 annual real interest is obtained from the Bank of Korea [45], and the interest rate (1.15%) is calculated.

3.3.2. COE (Cost of Electricity)

The Cost of Electricity (COE) is the total cost of producing 1 kW of electricity from a system, while the NPC is the sum of the present value of the total costs within a given period.

3.3.3. NPC (Net Present Cost)

Most of renewable energy projects require high installation, operation and management fees, thus, the Net Present Cost (NPC) is significant economic parameters for many renewable energy projects and criteria for decision makers.

3.3.4. Project Period

Most renewable energy projects require a long-term period because governments generally attempt to extend the harnessing of renewable energy for a very long time. In existing studies, projects last for 20 to 30 years. Thus, this study hypothesized a project lifetime of 25 years according to previous research.

3.4. Equipment Data

3.4.1. Photovoltaic

According to Kim *et al.* (2014) [14] and Yoo *et al.* (2014) [42], $1800 was applied for the initial costs and the replacement costs of solar panels while the annual O&M cost per 1kW capacity was $25. The lifetime of a PV panel was set as 25 years while a derating factor of 0.8 was applied on the electric generation from each PV panel. Applying a derating factor enhances the accuracy of the simulation as this factor considers the reduction of the panel's productivity caused from the changing effects of temperature and foreign matter, such as dust, on the panels by 20. This study also considers the air temperature shifts, thus there is a decrease in power efficiency of 0.5%/°C. We assumed that all panels were designed as fixed at 30°, 20% of reflection percentage without tracking system. The range of sensitivity test of simulation analysis was from 0 to 500 units.

3.4.2. Wind Turbine

We chose the Generik10 kW AC wind turbine model for our simulation. $14,500 and $12,500 were applied for the initial costs and the replacement costs of wind turbines respectively while the annual O&M cost of a turbine was $200 [42]. The lifetime of a turbine and the height of a hub were set as 15 years and 25 meters, respectively. [14].

3.4.3. Battery

We chose Surrette 6CS25P with the specifications of 6 V, 1.15 Ah, and 6.9 kWh [42]. Batteries were used to analyze and simulate the optimal hybrid system with 100% renewable energy generation. $249 was applied for the initial costs of installing and the replacement costs of the battery while the annual O&M cost was $1 per battery. The battery was presumed to be fully charged initially [10,14,39,40,45].

3.4.4. Converter

$80,000 was applied for the initial costs of installing and the replacement costs for the converter while the annual maintenance cost was $1000 per 100 kW [14,26,45]. The lifetime of the converter was set as 15 years, while the efficiency of a converter was assumed to be 90%. The capacity of a rectifier was assumed to be 85%, and it is designed to be equal to the capacity of the inverter.

4. Result

According to the simulation result, the optimized solution for Yeongjong Island consists of 11 wind turbines, 357 kW PV, a 56 kW converter, and 825 batteries. The detailed components information and optimized results are shown in Tables 1 and 2. Tables 3 and 4 show the information of total cost and annual cost. Table 5 shows the electricity production amount and system components. The predicted operating cost is $76,226/year, and predicted initial capital is $1,868,025, and calculated NPC and COE of optimized system is $3,516,052 and $0.545 per kWh respectively. The optimized system produces none of sulfur dioxide (SO_2), nitrogen oxide (NO), and carbon dioxide (CO_2) during electricity generation.

Table 1. Details of the simulation components.

Component	Model Type	Size	Capital Cost ($)	Replacement Cost ($)	Operation Management Cost ($/Year)	Lifetime (Years)
PV panel	-	1 kW	1800	1800	25	20
Wind turbine	Generic	1 unit	14,500	12,500	20	15
Battery	Surrette 6CS25P	1 unit	1229	1229	10	
Converter	-	1 kW	800	800	10	15

Table 2. The suggested optimal renewable power generation system.

Components	Index
Wind (number of turbines)	11
PV (kW)	357
Converter (kW)	57
Battery(number of batteries)	825
Grid (kW)	0
Operating Cost ($ per year)	76,081
Initial Capital ($)	1,861,625
Total NPC ($)	3,506,509
COE ($/kWh)	0.545

Table 3. NPC of the system.

Components	Capital ($)	Replacement ($)	O&M ($)	Salvage ($)	Total ($)
PV	642,600	511,238	192,960	−362,122	984,676
Wind	159,500	115,828	47,564	−34,438	288,455
Battery	1,013,925	1,654,517	178,366	−698,345	2,148,463
Converter	45,600	38,413	38,413	−11,421	84,916
System	1,861,625	2,319,996	431,214	−1,106,326	3,506,509

Table 4. Annualized costs of the system.

Components	Capital ($/Year)	Replacement ($/Year)	O&M ($/Year)	Salvage ($/Year)	Total ($/Year)
PV	29,722	23,646	8925	−16,749	45,544
Wind	7377	5357	2200	−1593	13,342
Battery	46,897	76,527	8250	−32,301	99,373
Converter	2109	1777	570	−528	3928
System	86,106	107,307	19,945	−51,171	162,187

Table 5. Annual electrical component production, load and quantity.

Component	Production (kWh/Year)	Fraction
PV array	466,291	88%
Wind turbines	65,395	12%
Grid purchases	0	0%
Total	531,685	100%
Load	**Consumption (kWh/Year)**	**Fraction**
AC primary load	297,597	100%
Total	297,597	100%
Quantity	**Value**	**Units**
Excess electricity	161,725	kWh/year
Unmet load	243	kWh/year
Capacity shortage	287	kWh/year
Renewable fraction	1.00	-

Figure 7 shows the summary of cash flow, and Figure 8 shows the average electricity production of the system.

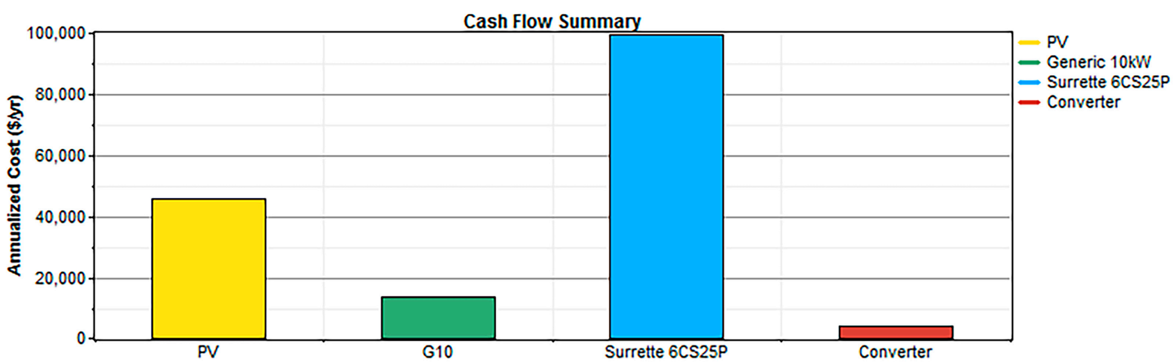

Figure 7. Summary of the cash flow.

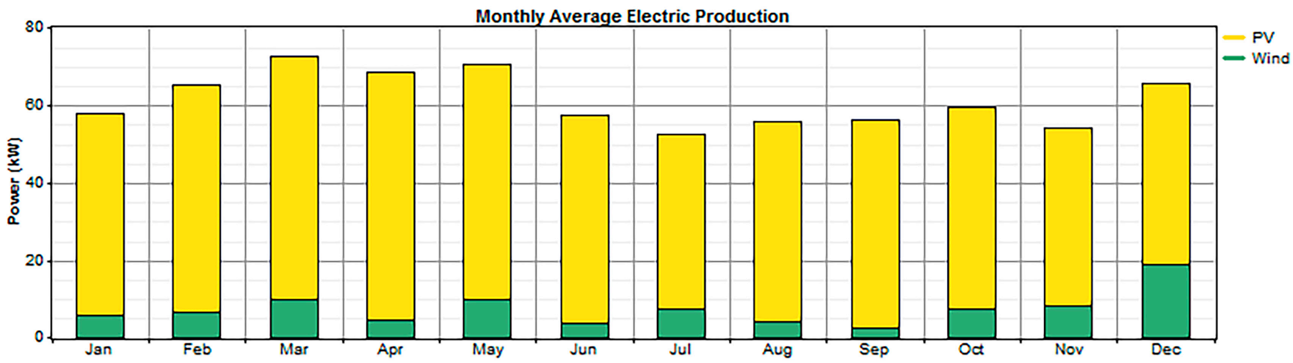

Figure 8. Average electricity production of the system.

According to Figure 7, batteries are the biggest cost. This is because our analysis is the 100% renewable energy based simulation. In case of 100% renewable energy based energy system, it will need a great number of batteries because no grid connection is taken into consideration.

Figures 9–12 depict the PV output, wind turbine output, battery bank state of charge and the inverter output of the converter, respectively.

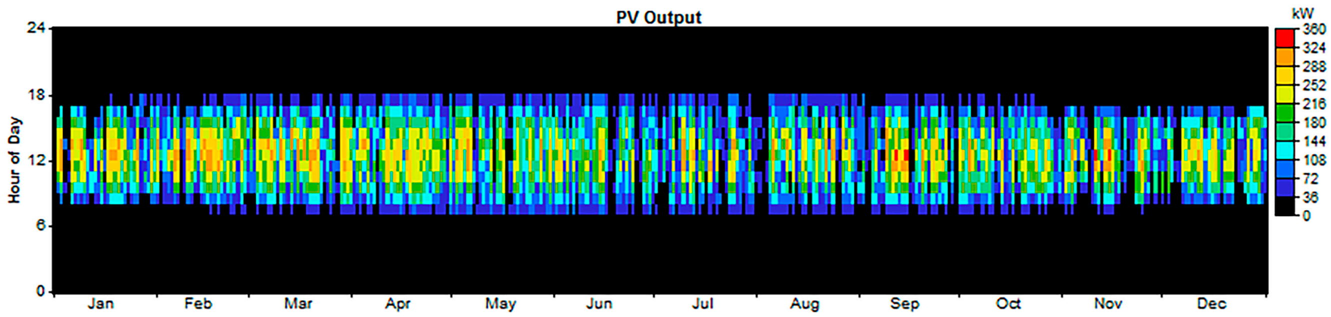

Figure 9. PV output.

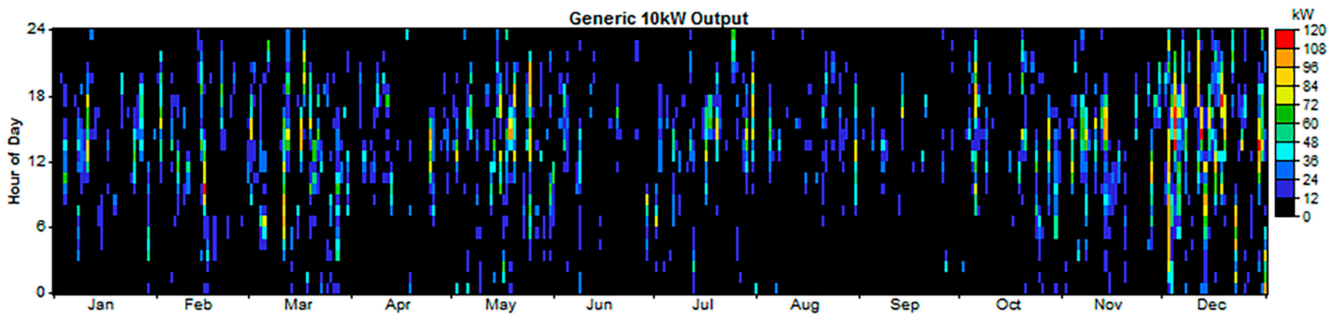

Figure 10. Wind turbine output.

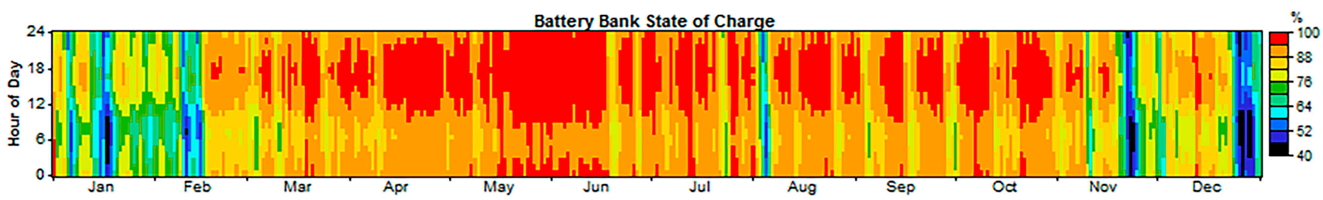

Figure 11. Battery bank state of charge.

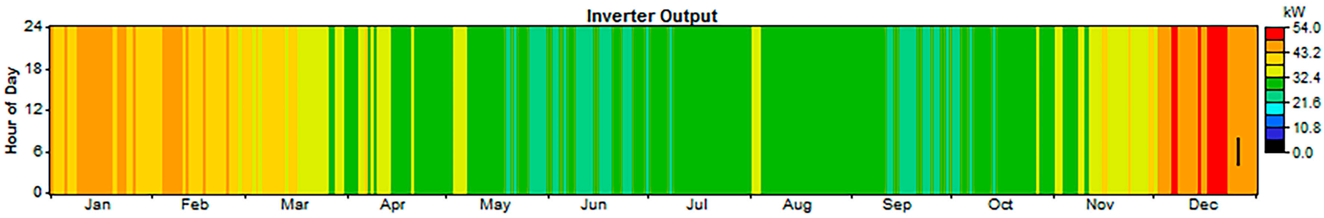

Figure 12. Inverter output of the converter.

Figure 9–12 show the each component is operating normally. In case of PV, the average output from April to June is greater than October–December period. However in case of wind-turbines, total output is greatest in December and lowest in September. Battery bank state of charge is highest from May from June in line with PV output; inverter output of converter is greatest in December in line with wind turbine output.

According to the research results, it is economically feasible to replace fossil fuel energy with renewable energy in 1/1000 scales. This means that one district of Yeongjong island could be independently operated by renewable energy. Therefore, the Yeongjong Island government should gradually expand the use of renewable energy. The present energy policy of Yeongjong Island primarily focuses on fossil fuel and grid connection. However, according to the research results, the wind power generation of Yeongjong Island shows suitable feasibility, particularly for the NPC. Therefore, the Yeongjong Island government should enlarge the renewable energy ratio.

5. Conclusions and Implication

Yeongjong Island was an unwatched location for renewable energy development until it succeeded in introducing many mega structures, such as an international airport, a mega resort, a theme park, and a new town. In the near future, Yeongjong Island will encounter the great challenge of a sustainable energy supply and development. According to research results, renewable energy has many more advantages for Yeongjong Island for the following reasons:

First, a renewable energy station has a lower cost and shorter construction period than other energy stations. Although Sihwa Lake near Yeongjong Island, the world's largest tidal power generation station, produces large amounts of electricity with no pollution, the station is not economically feasible because of its enormous construction cost and lengthy construction period. Furthermore, offshore generation necessitates higher costs on a grid connection than a common grid connection does, and an offshore wind turbine has much more expensive installation and operation management. Second, the renewable energy station produces no carbon dioxide and has no risk of any other environmental pollution. Combined cogeneration is economically feasible; however, it produces considerable amounts of carbon dioxide per kWh. Combined cogeneration may be feasible in the initial stage, but the carbon dioxide problem will be much more serious if Yeongjong Island needs two or three more combined cogeneration stations for electricity supply in the future. Third, renewable energy generation is a resident-friendly system. Because Ulsan in Korea has had nuclear station malfunction problems caused by corruption local residents strongly oppose the construction and use of nuclear generation. Additionally, tidal generation has encountered strong resistance because it will destroy the ecosystem. Finally, renewable energy generation will positively affect the development of the new growth engine industry. The South Korean government has designated renewable energy and renewable energy-related industries as a "new-growth engine industry" since 2011. To construct Yeongjong Island's renewable energy station, a huge number of local firms will be needed to engage in the new-growth engine industry. Thus, the adoption of renewable energy in Yeongjong Island will nurture local firms in a new growth engine industry and will have a positive effect on its local economy.

Currently, the local government invests solely in a "green home project" that provides a subsidy for PV installations for residential use and passively invests in a renewable energy park construction or sets strict policies on renewable energy duties. However, South Korea is the eighth-largest energy-consuming country, and the electricity demand of Yeongjong Island is increasing dramatically every year. Thus, it is very important to adopt more renewable energy for Yeongjong Island. Furthermore, the COE of South Korea is anomalously lower than its production cost. This deficit has been covered by the government budget and taxes. This is not a suitable structure for electricity supply. This structure will create more deficits, and this burden will be experienced by public enterprise, local government, and residents through a progressive tax. Thus, the adoption of a micro grid system with a hybrid optimized renewable energy system with economically feasible NPC and COE is a more effective and suitable means for an emerging island with regard to both tangible (construction fee and period) and intangible aspects (environmental protection, resident resistance, and CO_2 emission).

6. Limitation

First, the generalization of the research results may be difficult because the current study was conducted in a particular location in South Korea. Solar, wind energy, cost, the specification of the hybrid system, and economics may be different from other countries. However, the research method may be applicable to other countries for which we can obtain the load profile and data on renewable energy sources.

Second, we cannot ensure that the system we discuss is always perfectly reliable. An island's stand-alone power generation system may be unreliable when the system suffers from a disaster. Therefore, the hybrid system that we discuss in the paper has many batteries. The energy storage system, which includes a large-scale battery, allows power generators to send extra produced electricity through the grid to an electricity storage system that subsequently becomes an energy supplier when electricity is needed. It is important to make a distributed system reliable and to match supply and demand. An energy storage system can be an option to provide a reliable energy supply.

Third, according to the HOMER simulation result that we use in this research, the optimal system is one that we suggest is mathematically optimal for the real data. However, there may be other optimized solutions that cost less and that are not indicated by the HOMER simulation.

Fourth, the wind turbines are used in the simulation for 10 kW systems, which is basically a household-size turbine. In HOMER, we can build a larger system using Vestas V82 (1650 kW AC). However, we consider three main points. First, we assumed a scaled-down hybrid system. Second, a 10 kW wind turbine was primarily used in previous studies. Third, we want to find a more accurate value that is equal to the optimal value using small unit turbines. Future studies can use larger wind turbines when it is not necessary to scale down the load.

Finally, because many panels and turbines should be made, a large-scale hybrid system can be more economical because of economies of scale. However, HOMER does not consider the economy of scale during the simulation. Therefore, a scaled-down process does not cause issues within the study.

Author Contributions

Seoin Baek analyzed the data and completed the first draft, Heetae Kim wrote the energy policy part and revised the paper, Hyun Joon Chang revised the final version of paper.

Conflicts of Interest

The authors declare no conflict of interest.

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