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*Article*

# Optimized Renewable and Sustainable Electricity Generation Systems for Ulleungdo Island in South Korea

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**Abstract:** The South Korean government has long been attempting to reduce the nation's heavy reliance on fossil fuels and increase environmental safety by developing and installing renewable power generation infrastructures and implementing policies for promoting the green growth of Korea's energy industry. This study focuses on the use of independent renewable power generation systems in the more than 3000 officially affirmed islands off Korea's coast and proposes a simulated solution to the electricity load demand on Ulleungdo Island that incorporates several energy sources (including solar, batteries, and wind) as well as one hydro-electric and two diesel generators. Recommendations based on the simulation results and the limitations of the study are discussed.

**Keywords:** HOMER; optimal solution; Ulleungdo Island; renewable energy

## 1. Introduction

While public and industrial awareness of energy and environmental issues has continued to grow, governments across the globe have adopted measures to further the dissemination and diffusion of renewable energy resources [1]. For example, the South Korean government has installed renewable power generation facilities to lower the nation's high dependency on fossil fuels and reduce greenhouse gas emissions [2]. In addition, governments provide financial assistance for the installation of renewable energy facilities to islands that intend to become an independent energy region [3,4]. For example, the local government of Spain's El Hierro Island recently achieved 100% renewable power generation, providing 158% of the island's electricity demand. This island, with an area of 278 $km^2$ and a population of 10,000, constructed a hydro-wind power generation system comprising a hydro station, pumping station, hydro turbines, wind turbines, desalination plants, and upper and lower reservoirs. This system can save about 6000 tons of diesel fuel and eliminate approximately 19,000 tons of carbon dioxide emissions, about 400 tons of nitrogen oxide, about 100 tons of sulfur dioxide, and approximately 7000 kg of particulate every year [5,6]. As another example, Jeju Island, South Korea's biggest island, officially announced that it would have an independent energy system by 2030 [7]. However, because the island's government is considering only renewable energy facilities, there is no systematic energy solution or even goal for the island.

Moreover, South Korean territory includes over 4000 islands. Establishing self-sufficient renewable power generation systems for them, which will subsequently lower the maintenance costs of the electricity grid between the mainland and the islands, is an urgent energy demand issue for South Korea [8].

This study examines an independent optimized renewable power generation system for a South Korean island using its electricity consumption data. The study focuses on Ulleungdo Island, situated about 140 km east of the mainland. This study uses the hybrid optimization of multiple energy resources (HOMER) software developed by the National Renewable Energy Laboratory (NREL) to simulate a renewable power generation system for Ulleungdo Island within the limits of the relevant economic parameters, the net present cost (NPC), and the cost of energy (COE). To this end, the following research question is addressed:

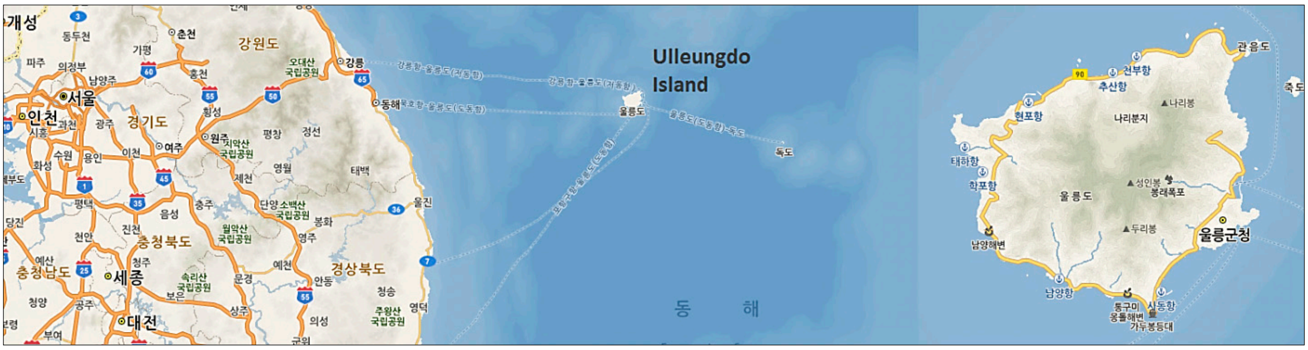
Do we propose the optimal and least expensive renewable power generation system, including compared to the current system?

## 2. Status of Ulleungdo Island

### 2.1. Location and Population

Ulleungdo Island is located about 140 km east of mainland South Korea, at 37.3 north latitude and 130.52 east longitude. The area of the island is about 72.86 $km^2$. Figure 1 shows the geographical location of the island. It comprises about 11,000 residents and 5000 households.

**Figure 1.** Geographical location of Ulleungdo Island.



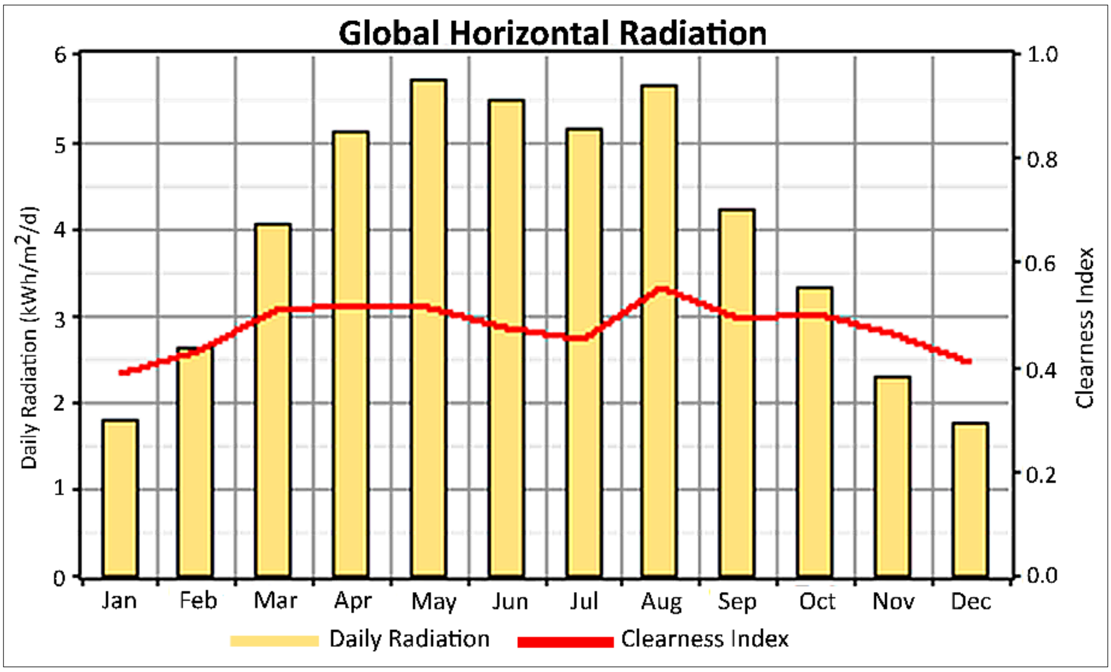

## *2.2. Load Information*

The current energy system of the island is powered primarily by two diesel generators (8000 kW and 4000 kW) and one hydro turbine (700 kW). Diesel fuel is supplied by the mainland. The Korea Electric Power Corporation (KEPCO) data show that the island's annual electricity use totals 111,000 kWh/d. Therefore, this study assumes the island's average energy demand to be 4611 kWh, with a peak energy demand of 5428 kW; the calculated load factor is 0.849.

## *2.3. Solar Energy*

This study uses solar data collected in 2013 by the Korea Meteorological Administration (KMA) as inputs for the solar clearness and daily radiation indices the HOMER software requires. The average annual solar clearness and average daily radiation are 0.486 and 3.931 kWh/m$^2$/d, respectively. Figure 2 depicts the island's monthly solar energy production.

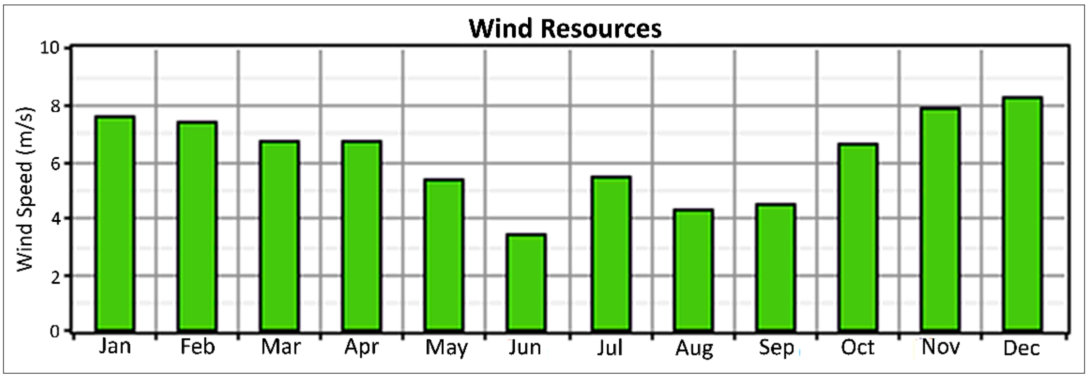
**Figure 2.** Monthly solar energy production on Ulleungdo Island.



### *2.4. Wind Speed*

Data on wind energy collected by the Korea Meteorological Administration (KMA) in 2013 [9] indicate that the island's annual average wind speed is 6.165 m/s. Figure 3 shows the island's monthly average wind speeds.

**Figure 3.** Monthly wind speed on Ulleungdo Island.




### *2.5. Hydro Resources*

A hydro turbine is included in the simulation because one has been consistently used on the island, with an annual average stream flow of 830.3 L/s.

## 3. Key Parameters for the Economic Analysis

### *3.1. Annual Real Interest Rate*

The HOMER software uses the annual real interest rate for greater accuracy. The 2013 annual real interest is obtained from the Bank of Korea [10], and the interest rate (3.02%) is calculated using the equations introduced by Dursun [11].

### *3.2. Cost of Energy (COE) and Net Present Cost (NPC)*

In general, the COE is the product of the amount of electrical energy produced by the system in kWh and the system's total annual cost. The total annual cost is the total cost of the system components along with other maintenance costs. The economic feasibility of the system is evaluated based on the COE level.

The NPC is a significant economic output. Previous studies have pointed out that the lifecycle cost fully covers the expense of establishing and operating the system. This study hypothesizes a project lifetime of 20 years.

### *3.3. Diesel Price*

Since the island's electricity system is mainly powered by two diesel generators and one hydro turbine, the price of diesel is integral to an economic evaluation of the island's current and future electricity generation systems. The diesel price used for the analysis is $1.8 per liter (according to 2014 data provided by the Korea National Oil Corporation and the Bank of Korea) [10].

**Table 1.** Details of the simulation components [7,11–15].

| Component | Model Type | Size or Quantity | Capital Cost ($) | Replacement Cost ($) | Operation & Management Cost ($/year) | Lifetime | Other |
| --- | --- | --- | --- | --- | --- | --- | --- |
| PV panel | - | 1 kW | 1800 | 1800 | 25 | 20 years | 80% derating factor; 37.48° slope with no tracking system; a range of 0 to 30,000 PW is considered. |
| Wind turbine | Generic 10 kW | 2 units | 29,000 | 25,000 | 400 | 15 years | 25 m hub height; a range of 0 to 2500 turbines is considered. |
| Battery | Surrette 6CS25P | 1 unit | 1229 | 1229 | 10 | - | 6 V nominal voltage; 1156 Ah (6.94 kWh) nominal capacity; 9645 kWh lifetime throughput; a range of 0 to 50,000 battery-units is considered. |
| Diesel generator 1 (currently operating) | - | 1 kW | 0 | 450 | 0.2 | 15,000 h | 30% minimum load ratio; the capacity of the current diesel generator is 8000 kW. |
| Diesel generator 2 (currently operating) | - | 1 kW | 0 | 450 | 0.2 | 15,000 h | 30% minimum load ratio; the capacity of the current diesel generator is 4000 kW. |
| Hydro turbine (currently operating) | - | - | 0 | 0 | 0 | 25 years | 95 m available head, 75% efficiency, and 15% pipe head loss. |
| Converter | - | 1 kW | 800 | 800 | 10 | 15 years | 90% efficiency; a range of 0 to 5000 kW is considered. |

## 4. Renewable Power Generation Systems

The HOMER software requires inputs for the costs of installation, replacement, operation, and management of the system components. Table 1 summarizes the cost of each component.

## 5. Results

This study employs two diesel generators, one hydro turbine, 1725 wind turbines, photovoltaic (PV) panels, a converter, and batteries to build an optimized renewable power generation system on Ulleungdo Island. The simulated optimization results are reported in Table 2. Information on the simulated total and annual cost is presented in Tables 3 and 4, and the electricity production and quantity of system components are reported in Table 5.

**Table 2.** Proposed renewable power generation system for Ulleungdo Island.

| Components | Index |
|---|---|
| Hydro (kW) | 700 |
| Wind (# of turbines) | 1725 |
| PV (kW) | 31,065 |
| Diesel generator 1 (currently used, kW) | 8000 |
| Working hours (diesel generator 1) | 64 |
| Diesel generator 2 (currently used, kW) | 4000 |
| Working hours (diesel generator 2) | 474 |
| Consumed diesel (L) | 696,396 |
| Battery (# of units) | 32,765 |
| Converter (kW) | 5975 |
| Initial Capital ($) | 125,977,680 |
| Operating Cost ($/year) | 6,250,551 |
| Total NPC ($) | 234,819,440 |
| COE ($/kWh) | 0.334 |
| Ren. Frac. | 0.97 |

**Table 3.** Total cost of operating the simulated system for 20 years.

| Components | Capital ($) | Replacement ($) | O&M ($) | Fuel ($) | Salvage ($) | Total ($) |
|---|---|---|---|---|---|---|
| PV | 55,917,000 | 30,959,904 | 13,523,491 | - | −20,029,718 | 80,370,672 |
| Wind | 25,012,500 | 13,840,154 | 6,007,538 | - | −3,432,793 | 41,427,396 |
| Hydro | - | - | - | - | - | - |
| Generator 1 | - | - | 1,783,107 | 5,295,827 | −1,535,981 | 5,542,954 |
| Generator 2 | - | - | 6,603,068 | 16,531,792 | −180,535 | 22,954,328 |
| Battery | 40,268,184 | 48,052,596 | 5,705,420 | - | −17,629,630 | 76,396,552 |
| Converter | 4,780,000 | 3,068,102 | 1,040,436 | - | −760,985 | 8,127,552 |
| System | 125,977,688 | 95,920,752 | 34,663,060 | 21,827,620 | −43,569,644 | 234,819,456 |

**Table 4.** Annual cost of operating the simulated system.

| Components | Capital ($/year) | Replacement ($/year) | O&M ($/year) | Fuel ($/year) | Salvage ($/year) | Total ($/year) |
|---|---|---|---|---|---|---|
| PV | 3,211,194 | 1,777,961 | 776,625 | - | −1,150,264 | 4,615,517 |
| Wind | 1,436,415 | 794,811 | 345,000 | - | −197,138 | 2,379,087 |
| Hydro | - | - | - | - | - | - |
| Generator 1 | - | - | 102,400 | 304,128 | −88,208 | 318,320 |
| Generator 2 | - | - | 379,200 | 949,386 | −10,368 | 1,318,218 |
| Battery | 2,312,516 | 2,759,558 | 327,650 | - | −1,012,432 | 4,387,292 |
| Converter | 274,505 | 176,195 | 59,750 | - | −43,702 | 466,748 |
| System | 7,234,631 | 5,508,525 | 1,990,626 | 1,253,514 | −2,502,112 | 13,485,182 |

**Table 5.** Electrical production and quantity of components in the simulated system.

| Component | Production (kWh/year) | Fraction |
|---|---|---|
| PV panels | 39,623,320 | 54% |
| Wind turbines | 28,159,934 | 38% |
| Hydro turbine | 3,675,421 | 5% |
| Diesel generator 1 | 512,000 | 1% |
| Diesel generator 2 | 1,503,026 | 2% |
| Total | 73,473,696 | 100% |
| Quantity | Value | Units |
| Excess electricity | 25,494,698 | kWh/year |
| Unmet load | 0.0886 | kWh/year |
| Renewable fraction | 0.973 | - |

The simulation results indicate that the proposed system can significantly reduce the diesel consumption and that the reliability of the power generation system can be improved by utilizing all recommended components (*i.e.*, two diesel generators, one hydro turbine, 1725 wind turbines, PV panels, a converter, and batteries). Figure 4 shows the cash flow summary, and Figure 5 depicts the average electricity production. Figure 6 summarizes the proposed system's battery data. The proposed system can also save 3683 kg of sulfur dioxide, 40,391 kg of nitrogen oxide, 341 kg of particulate, 501 kg of unburned hydrocarbons, 4527 kg of carbon monoxide, and 1,833,841 kg of carbon dioxide waste every year.

**Figure 4.** Summary of cash flow.

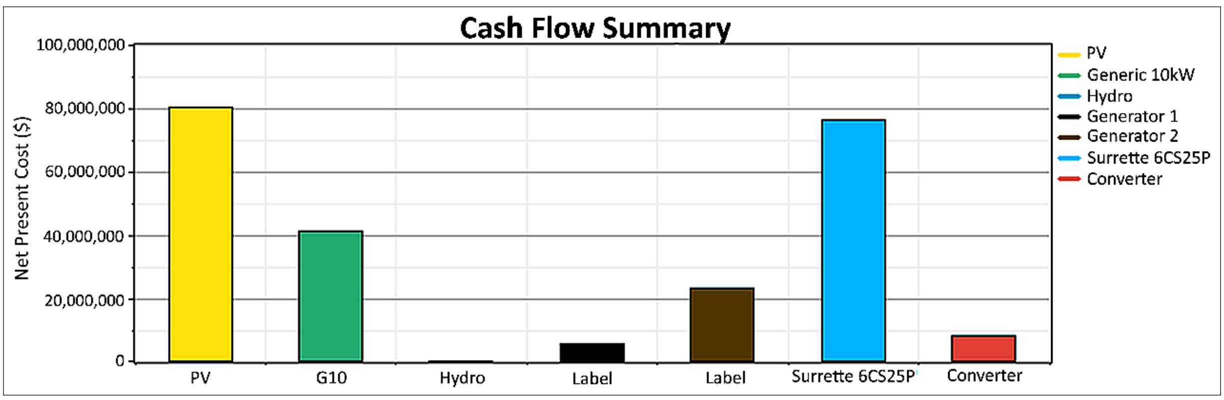


**Figure 5.** Average electricity production of the system.

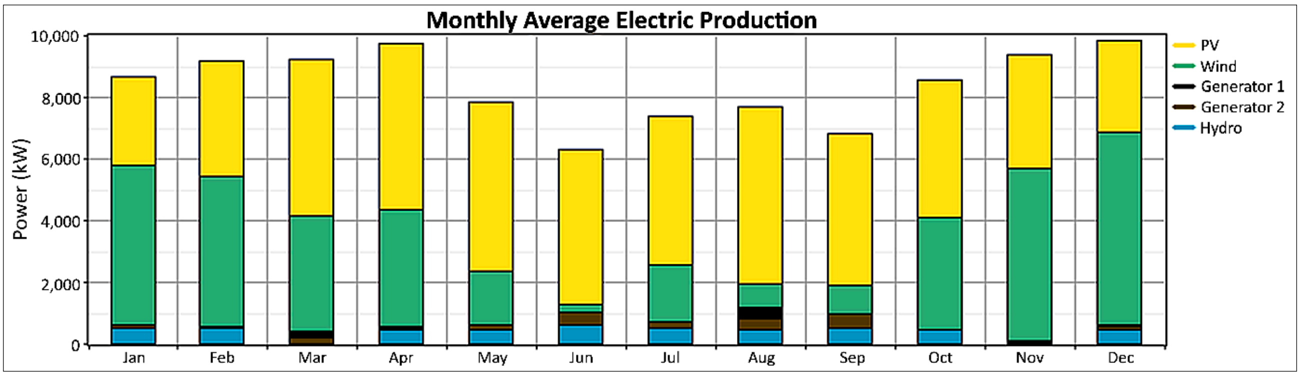
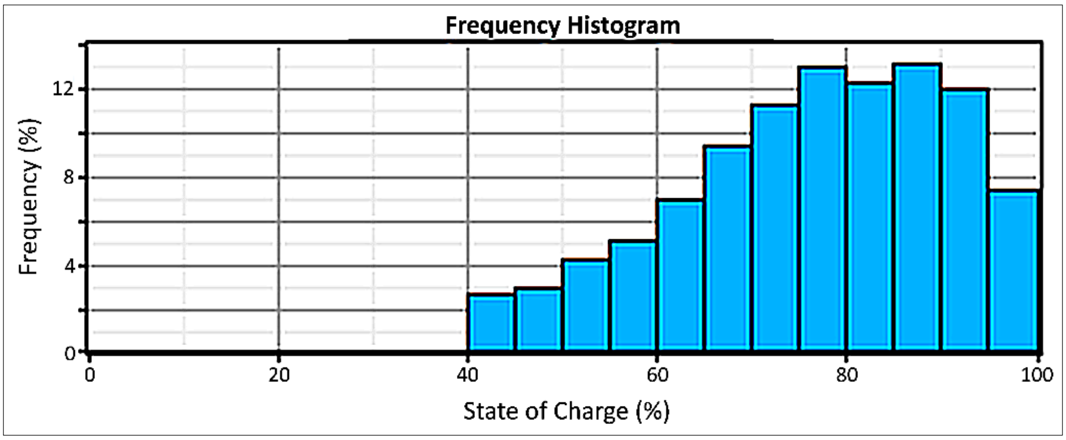



**Figure 6.** Frequency histogram of the batteries in the simulated system.




## 6. Conclusions

This study proposes the configuration of an optimized renewable power generation system for Ulleungdo Island using HOMER software. The main findings of the simulation are as follows:

- The suggested optimal solution consists of 1725 wind turbines (generic 10 kW model), 31,065 kW PV panels, a 5975 kW converter, 32,765 batteries (Surrette S6CS25P), and the retention of the two operating diesel generators (8000 kW and 4000 kW) and hydro turbine (700 kW).
- The simulation results predict an operating cost of $6,250,551 per year, an initial capital of $125,977,680, a total NPC of $234,819,440, and a renewable fraction of 97% at a $0.334 per kWh COE.
- Diesel fuel use is significantly reduced, from over 14,500,000 L to less than 700,000 L, in the simulation. It also reduces other costs, such as that of transporting fuels.

The simulation indicates that installing the renewable power generation system on the island would require a huge initial capital. However, the system would significantly reduce overall costs in the long term, including operation and maintenance expenditures. In addition, as the two diesel generators provide only about 3% of the total power, the system could eliminate them and employ more battery units and other facilities instead. Therefore, this study conducts further simulations to determine an optimal renewable power generation system that omits the diesel generators. These simulations indicate that the optimal system without the generators shows similar degrees of COE ($0.348) and

NPC ($249,192,221). Thus, the diesel generators could be eliminated after their lifetimes have expired. The following points should be considered for the implementation of the system:

- Achieving the optimal level will require that gradual development plans be prepared for the island.
- Reducing the island's dependency on diesel generators will require that the reliability of its electricity system be improved and that further planning consider various other energy sources.
- After a certain level of renewable energy use has been achieved, the local government and island communities should aim to install more renewable power generation facilities as an alternative to the current diesel generators.

## 7. Limitations

This study has several limitations. First, it omits some relevant economic costs, such as that of transporting diesel [16]. Second, it fails to discuss policies and plans implemented by the South Korean government to support renewable power generation systems [17,18]. For instance, the government actively enforces its renewable portfolio standard (RPS) for local areas [19] and plans to begin managing and improving its carbon-related systems soon. Third, this study does not consider issues or theories concerning national energy industries, of which the learning effect and economies of scale are among the most significant [20,21]. Fourth, this study was conducted on a specific island in South Korea, perhaps limiting the generalizability of its results. Fifth, several renewable power generation systems, such as heat recovery facilities and geothermal power generation facilities, were not considered. Both the findings of this study and its limitations can be used as a basis for future work on similar questions.

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## Author Contributions

Kyeongsik Yoo and Eunil Park conducted the simulation and drafted the majority of the manuscript. Heetae Kim and Jay Y. Ohm contributed to data collection and drafting of the manuscript. Taeyong Yang, Ki Joon Kim, Hyun Joon Chang and Angel P. del Pobil contributed to analysis and interpretation of data.

## Conflicts of Interest

The authors declare no conflict of interest.

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