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Optimal Sizing and Comparative Analysis of Renewable Energy Integration for The Existing Microgrid System in Kadan Island

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Abstract

The rapid depletion of fossil fuels and the necessity for reduced carbon emissions have led to an increased focus on renewable energy resources. The existing microgrid system comprises solely a diesel generator and a small portion of hydropower. Currently, Kadan Island relies mainly on diesel generators to supply power, resulting in a significantly higher cost of energy in comparison to other areas. Furthermore, there is still not enough electricity available on the entire island of Kadan. However, research has shown that integrating renewable-based systems with storage technologies into existing systems can help mitigate these issues. Therefore, the main objective of this paper is to investigate the optimal size and operation of a hybrid renewable system on the Myanmar Islands. The optimization process will focus on minimizing the net present cost (NPC) and cost of energy (COE) of the selected location. Additionally, the island's network will be analyzed under normal operating conditions with different scenarios, and the best scenario for the existing microgrid on Kadan Island will be recommended.

A. Introduction

More than one billion individuals worldwide lack access to electricity, with a majority residing in remote rural areas of developing countries, particularly in Asian countries and parts of Asia, such as Myanmar. This is primarily due to the absence or instability of the national grid in these locations, which compels them to heavily rely on diesel generators to meet their energy needs. However, this reliance on diesel generators not only proves to be expensive and vulnerable to fluctuating fuel prices but also contributes to environmental pollution [1].

The integration of renewable energy resources into a microgrid system on an island has emerged as a viable solution to address the aforementioned issues. Integrating renewable energy sources like wind and solar power into tourist islands can effectively mitigate the adverse effects of electricity generation on the surrounding ecosystem. Furthermore, it is crucial to optimize the system to guarantee optimal performance, maximizing financial gains while reducing energy usage and environmental effects. Research on microgrid systems in island regions emphasizes the importance of comprehending load requirements and taking into account assessment factors like economic aspects, pollution, dependability, and geographic data in order to ascertain the size of the microgrid [2].

The availability of energy resources, the wide range of technology options, and the variability in cost of technology make project design decision-making difficult. In this investigation, HOMER, a software developed by NREL, is used to simulate a microgrid system. Fortunately, HOMER's optimization and sensitivity analysis algorithms offer a solution by streamlining the evaluation of numerous potential system configurations. With HOMER, users can input an hourly power consumption profile and align renewable energy generation with the required load. It allows for the assessment of micro-grid potential, optimal integration of renewable energy sources, the proportion of renewable sources to total energy, and mini-grid stability, especially for medium- to large-scale projects. Moreover, HOMER features an efficient optimization function that assists in determining the cost of different electricity supply scenarios [3].

To achieve cost reduction and scenario optimization, this feature allows for the utilization of different factors. In order to use HOMER effectively, the model requires inputs that define technology choices, component expenses, and resource availability. By simulating various system configurations or combinations of its components using these inputs, HOMER generates results that can be shown as a list of feasible setups ordered by cost of energy (COE) and net present cost. Additionally, HOMER provides simulation outcomes in a variety of tables and graphs, making it easier to compare and evaluate configurations based on their economic and technical advantages [5].

B. Research Method

To analyze the operational behavior of all possible scenarios, the assessment of renewable energy-based systems typically necessitates the application of pertinent criteria to on-site location data. The evaluation outlines, which included the site specifications, average electric load profile, system modeling, costs, and components of the hybrid system, were carried out in this research. Figure 1 depicts the block diagram of the research methodology.

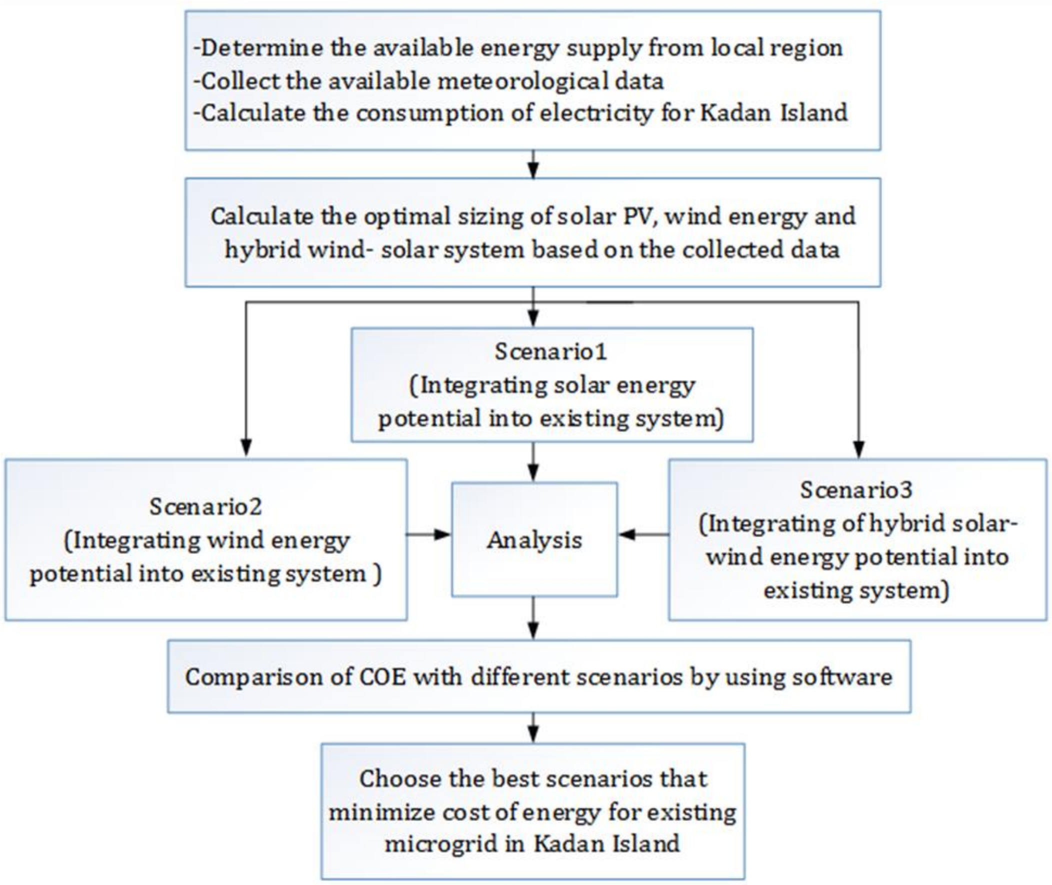

Figure1. Block Diagram of Research Methodology

C. Location and Electricity Demand Condition

In the coastal region of Tanintharyi in Myanmar, there are numerous islands, with Kadan being the largest among them. Kadan Island is characterized by its limited flat land and abundance of hills and mountains, all surrounded by the sea. In this research, Kadan Island has been chosen as the focal point. Situated in the southern part of Myanmar's Tanintharyi region, this isolated location is home to approximately 174,628 individuals. Spanning an area of 1838.48 square miles, Kadan Island comprises a total of 29,467 households, with 28,559 residing in rural areas and 908 in urban areas. The study area is positioned at North Latitude 12° 45' and East Longitude 98° 55'. The geographical placement of the study area can be observed in Figure 2.

Figure 2. Map of Kadan Island

1. Condition of Electricity Distribution in the Existing Microgrid

In the current microgrid system, power generation is provided by a 500kW diesel generator and a Francis turbine with a capacity of 270kW. The daily electricity demand varies according to the three primary seasons of summer, rainy, and winter. During the summer season, the six villages and four quarters are supplied with power for 24 hours using the diesel generator, as illustrated in Figure 3. In the rainy and winter seasons, the power supply is alternated between the diesel generator and the hydropower plant to meet the continuous demand of the six villages and four quarters, as shown in Figure 4.

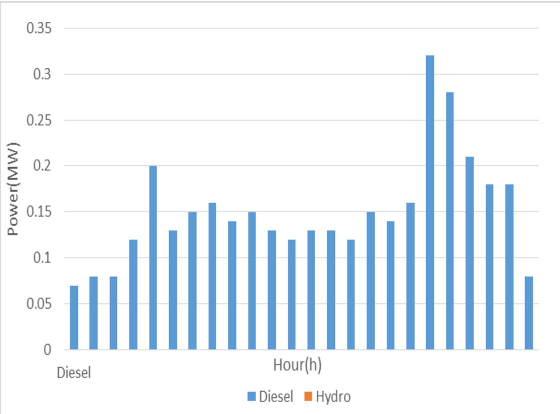

Figure 3. Hourly Load Demand of Existing System (for Summer)

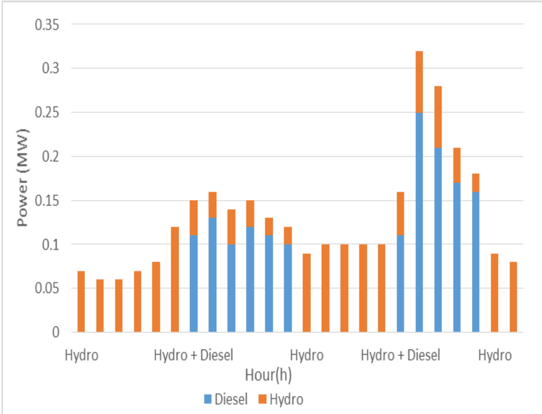

Figure 4. Hourly Load Demand of Existing System (for Rainy and Winter)

2. Energy Resource Assessment of Kadan Island

Kadan Island has the potential to be a suitable choice for harnessing renewable energy sources. The quantity of electrical energy generated by a solar power facility is primarily influenced by the presence of sunlight, whereas wind power relies on the velocity of the wind at its specific placement site. Solar and wind energy have been identified as viable sources for generating electricity on this island. The solar and wind data needed for assessing resources at the proposed location was obtained from the Surface Meteorology division of the National Aeronautics and Space Administration (NASA). The clearness index and average horizontal radiation for this location are described in Figure 5. The monthly average wind speed for the selected region is shown in Figure 6.

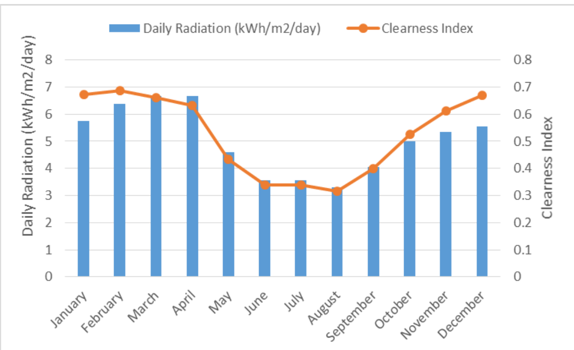

Figure 5. Solar Irradiation of Kadan Island

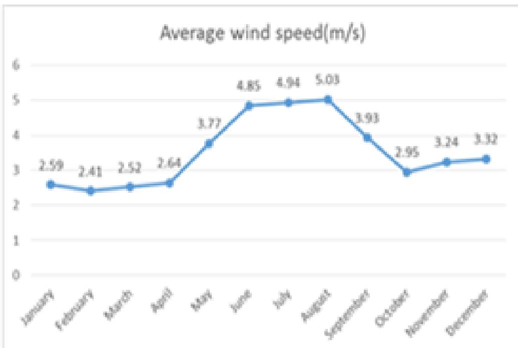

Figure 6. Wind Speed of Kadan Island

3. Load Demand for Proposed System

The load demand was evaluated for a total of 29467 households on the whole island of Kadan, located in Myeik district in the Tanintharyi region. This evaluation meticulously considered the anticipated requirements of the location, ensuring a thorough understanding of its future needs. As a result, it was determined that the daily electricity demand was 58.03 MWh, corresponding to an annual demand of 21180.95 MWh. Figure 7 illustrates the average load demand for the whole island of Kadan.

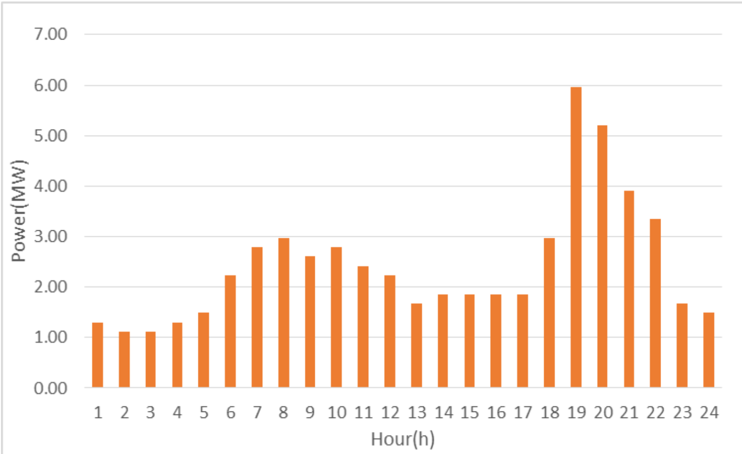

Figure 7. Hourly Load Demand of the Whole Island of Kadan

D. Mathematical Modeling of System Components

This research focuses on determining the most suitable configuration for the hybrid system, which includes photovoltaic (PV) energy, wind energy, hydro energy, a diesel generator, a battery, and a converter. In this study, the existing microgrid system has already been equipped with a 500kW diesel generator and a 270kW hydro turbine.

1. Solar PV

The photovoltaic system's design involves calculating the optimal quantity of PV modules that directly convert sunlight into DC power. The amount of power generated by each PV module in an hour can be represented using the formula [4]:

$$p_{PV}(t)=I(t)\times A\times \eta_{PV} \tag{1}$$

The solar insolation at hour t is represented by I (t) in kilowatts per square meter. The PV module area is denoted as A in square meters, and η_{pv} represents the efficiency of the PV module. The total power generated can be calculated using the following formula:

$$P_{PV}(t)=N_{PV}\times p_{PV}(t) \tag{2}$$

2. Wind Turbine

The generator's power output rises substantially once the wind speed surpasses the cut-in velocity. Specifically, the power output is directly related to the cube of the wind speed. In mathematical terms, the power produced by each wind turbine (p_{WT}) at time t can be represented as [7]:

$$p_{WT}(t) = \begin{cases} 0 & v(t) \leq V_{ci} (or) v(t) \geq V_{CO} \\ P_r \dfrac{v^3(t)-V^3_{ci}}{V^3_r-V^3_{ci}} & V_{ci}<v(t)<V_r \\ P_r & V_r<v(t)<V_{co} \end{cases} \quad (3)$$

The following is an expression of the total power produced:

$$P_{WT}(t)=N_{WT} \times p_{WT}(t) \quad (4)$$

Where the number of wind turbines is denoted by N_{WT}.

3. *Battery*

If the renewable power generated is sufficient to fulfill the load demand P_L (t), and any surplus is stored in the battery bank, the battery is considered to be in the charging state. The state of charge (SOC) at time t is expressed as follows [6]:

$$SOC(t)=SOC(t-1)\times(1-\sigma)+\frac{\left(P_g(t)-\dfrac{P_L(t)}{\eta_{inv}}\right)\times\eta_{bc}}{1000\times N_b\times C_b} \quad (5)$$

On the other hand, energy stored in batteries is used to make up for any shortage if renewable power is unable to meet load demand. Consequently, the mathematical representation of the state of charge (SOC) at time t is as follows [6]:

$$SOC(t)=SOC(t-1)\times(1-\sigma)-\frac{\left(\dfrac{P_L(t)}{\eta_{inv}}-P_g(t)\right)/\eta_{bd}}{1000\times N_b\times C_b} \quad (6)$$

Where, η_{bd} is the discharging efficiency of batteries.

4. *Bidirectional Converter*

In a hybrid AC/DC power system, power converters play a crucial role in converting DC to AC and vice versa. Wind turbines, PV panels, and batteries generate DC power, which needs to be converted to AC power using inverters in order to meet the AC load demand. The rated power of the inverter, P_{inv}, is calculated based on the peak AC load demand, $P_{peak\,AC}$, in the following manner [8]:

$$P_{inv}=\frac{P_{peakAC}}{\eta_{inv}} \quad (7)$$

Where η_{inv} is the inverter efficiency.

5. *Economic Parameters*

Economic analysis plays a crucial role due to its primary aim of minimizing costs. The net present cost (NPC) is calculated by the following equation [10]:

$$C_{NPC}=\frac{TAC}{CRF(i,N)} \quad (8)$$

Where, N represents the project lifetime (year),
i stands for the annual real discount rate (%),
TAC stands for total annualized cost ($/year).

According to [8], the capital recovery factor (CRF) is defined as follows in relation to both N and i:

$$CRF(i,N)=\frac{i(1+i)^N}{(1+i)^N-1} \tag{9}$$

The levelized cost of energy (COE) is defined as follows:

$$COE=\frac{TAC}{E_{anloadserved}} \tag{10}$$

Where $E_{anloadserved}$ is the system's total annual load (kWh).

At the end of the project's lifespan, the salvage value of each component is determined using the following formula [9]:

$$S=C_{rep}\frac{R_{rem}}{R_{comp}} \tag{11}$$

S indicates the amount of salvage .
C_{rep} is the component's replacement cost.
R_{rem} is the component's remaining life.
R_{comp} is the component's lifetime .

E. System Modeling with HomerPro Software

In this study, the different combinations of solar PV, wind, hydro, diesel generators, and batteries have been taken into consideration. To determine the optimal size of Kadan Island's existing microgrid, Homer Pro software is used after the design calculation of the selected system. The modeled configurations for each scenario are described in Figures 8 through 10.

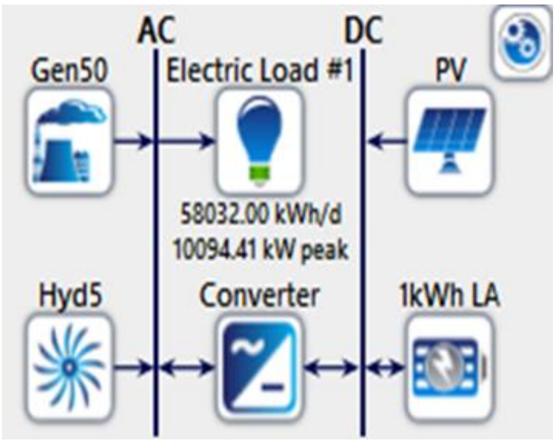

Figure 8. Integrating Solar Energy Potential (Scenario1)

In this research, the existing microgrid system, which consists of hydroelectric and diesel generators, is linked to the AC side of the network. In Figure 8, the DC side of the network is connected to the integration of solar PV and batteries. According to Homer Pro software results, the electricity consumption is 58032 kWh/day and the maximum demand is 10094.41 kW.

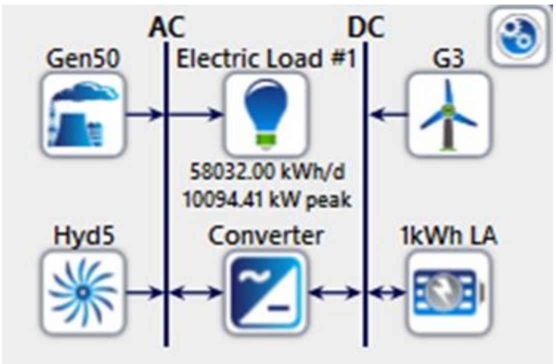

Figure 9. Integrating Wind Energy Potential (Scenario2)

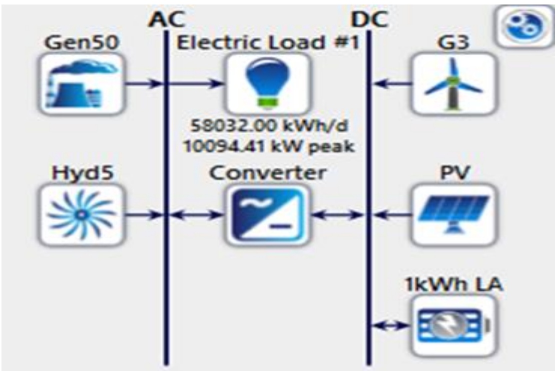

Figure 10. Integrating Hybrid Solar-Wind Energy Potential (Scenario3)

Figure 9 illustrates the integration of wind energy and batteries into the existing system, with the wind turbine and batteries connected to the DC side. Additionally, the integration of solar PV, wind energy, and batteries is also connected to the DC side, as depicted in Figure 10. A converter is utilized to convert DC to AC, and the battery is employed for storing electrical energy. Moreover, the battery can contribute to power quality improvement due to the intermittent nature of solar and wind power.

F. Simulation Results and Comparison of Different Scenarios

The optimization results of the three different scenarios are shown in the following Tables 1, 2, and 3. Grid connection is not considered in any of the scenarios due to the lack of access to the electrical grid in this area. While a grid-connected hybrid system offers lower energy costs, it requires a longer development time and comes with high installation costs. A detailed description of each scenario's outcomes can be found below.

Scenario 1: PV/Diesel/Hydro/Converter/Battery

The first scenario considered in this analysis is a hybrid PV/diesel/hydro/converter/battery system. The system is composed of 22345 kW of solar PV, an 8904 kW converter, a 26277 kWh battery, a 500 kW diesel generator, and a 270 kW hydro turbine. In this combination, the initial cost, operating cost, and COE were found to be $6.67 million, $1.08 million, and $0.106

per kWh, respectively. The total expense of the system is $20.7 million. Table 1 shows the Homer simulation results for PV, diesel, hydro, converter, and battery combinations (Scenario 1). Figure 11 shows the cost summary for scenario 1.

Table1. Scenario 1

Scenario 1 (PV+Hydro+DG+Battery+Converter)		
Component Size	PV (kW)	22,345
	Diesel Gen(kW)	500
	Battery(kWh)	26,277
	Hydro (kW)	270
	Converter(kW)	8,904
Cost	NPC ($ in M)	20.7
	COE($)	0.106
	Operating cost ($ in M per year)	1.08
	Intial capital($ in M)	6.67
System	Ren frac(%)	84.8
	Total fuel(L/yr)	714,730
Diesel Generator	Hours	5,246
	Production(kWh)	2,300,992
	Fuel (L)	714,730
	O&M Cost ($/yr)	5,246
	Fuel cost($/yr)	571,784
PV	Capital cost ($)	4,062,674
	Production(kWh/yr)	34,133,428
Battery	Autonomy (hr)	6.53
	Annual Throughput(kWh/yr)	5,047,843
	Nominal Capacity(kWh)	26,298
	Usable Nominal Capacity(kWh)	15,779
Converter	Rectifier Mean output (kW)	0
	Inverter mean output(kW)	1,465

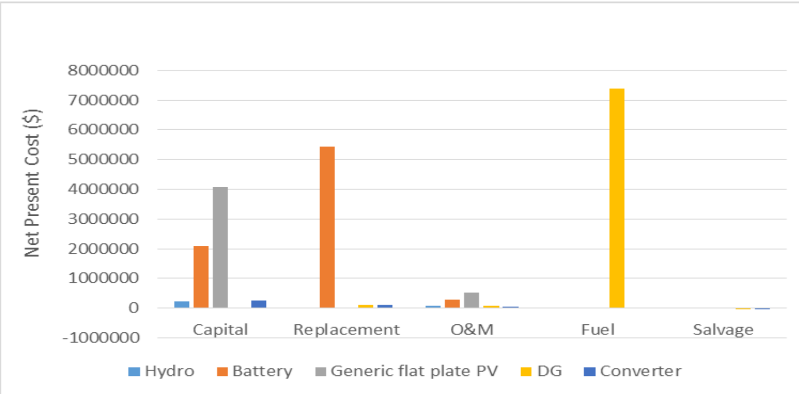

Figure11. Cost Summary of PV/Diesel/Hydro/Converter/Battery Configuration.

Scenario2: Wind/Diesel/Hydro/Converter/Battery

The second scenario studied in this analysis is a hybrid wind/diesel/hydro/converter/battery system. The system includes an 119391 kW WTG, a 500 kW DG, a 270 kW hydro turbine, a 16104 kW converter, and a 56493 kWh battery. The initial capital cost, COE, and net present cost (NPC) were higher in scenarios 2 than in scenarios 1. The total cost of the system is $30.4 million. The system is not economically feasible due to its high cost of energy (COE) and initial costs, as well as the significant amount of excess electricity observed. Table 2 shows the Homer simulation results for wind, diesel, hydro, converter, and battery combinations (Scenario 2). Figure 12 shows the cost summary of scenario 2.

Table 2. Scenario 2

Scenario 2 (Wind+Hydro+DG+Battery+Converter)		
Component Size	Wind (kW)	119,391
	Diesel Generator(kW)	500
	Battery(kWh)	56,493
	Converter(kW)	16,104
	Hydro (kW)	270
Cost	Cost of Energy ($)	0.150
	NPC ($ in Million)	30.4
	Intial capital cost ($ in Million)	17.2
	Operating cost ($ in M per year)	1.03
System	Ren fraction (%)	89.3
	Total fuel cost (L/yr)	523,132
Diesel Generator	O&M Cost ($/yr)	3,832
	Fuel (L)	523,132
	Fuel cost($/yr)	418,505
	Production(kWh)	1,684,628
	Hour	3,832
Wind	Production(kWh/yr)	54,638,916
	O&M cost ($)	119,391
	Capital cost ($)	11,939,100
Battery	Usable Nominal Capacity(kWh)	33,923
	Annual Throughput(kWh/yr)	4,681,914
	Nominal Capacity (kWh)	56,538
	Autonomy (hr)	14
Converter	Inverter Mean output (kW)	1,603
	Rectifier mean output(kW)	0

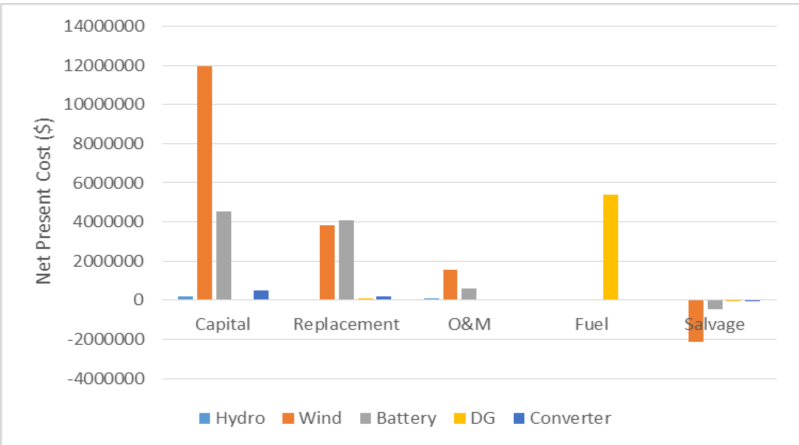

Figure12. Cost Summary of Wind/Diesel/Hydro/Converter/Battery Scheme.

Scenario3: PV/Wind/Diesel/Hydro/Converter/Battery

The third scenario considered in this analysis is a hybrid PV/Wind/Diesel/Hydro/Converter/Battery microgrid system. A 13378kW PV system, a 23430kW wind turbine, a 500kW diesel generator, a 270kW hydro turbine, a 6345kW converter, and a 19228kWh battery compose this system. The overall expense of the system amounts to 18.8 million dollars. In comparison to the previous two scenarios, it is the most cost-effective. Table 3 shows the Homer simulation results for PV, wind, diesel, hydro, converter, and battery combinations (Scenario 3). Figure 13 describes the cost summary of scenario 3.

Table 3. Scenario 3

Scenarios 3 (PV+Wind+Hydro+DG+Battery+Converter)		
Component Size	PV (kW)	13,378
	Wind Power (kW)	23,430
	Hydro Power (kW)	270
	Battery (kWh)	19,228
	Converter (kW)	6,345
	DG (kW)	500
Cost	Net Present Cost (Dollar in Million)	18.8
	COE(Dollar))	0.090
	Operating Cost ($ per year)	930,119
	Initial Capital Cost ($ in Million)	6.74
System	Ren frac (percentage)	87.5
	Total Fuel Cost (Litre/yr)	622,779
Diesel Generator	Production(kWh)	2,008,600
	Fuel(Litre)	622,779
	Hours	4,511
	Fuel cost($/year)	498,223
	O& M cost ($/year)	4,511
PV	Production(kWh/year)	20,436,174
	Capital Cost (Dollar)	2,432,382
Wind	Operation & Maintenance Cost ($)	23,430
	Capital cost($)	2,343,000
	Production(kWh / yr)	10,722,666
Battery	Nominal Capacity(kWh)	19,243
	Annual Throughput(kWh/yr)	3,806,124
	Usable Nominal Capacity(kWh)	11,546
	Autonomy (hours)	4.78
Converter	Rectifier output (kW)	0
	Inverter mean output(kW)	1,609

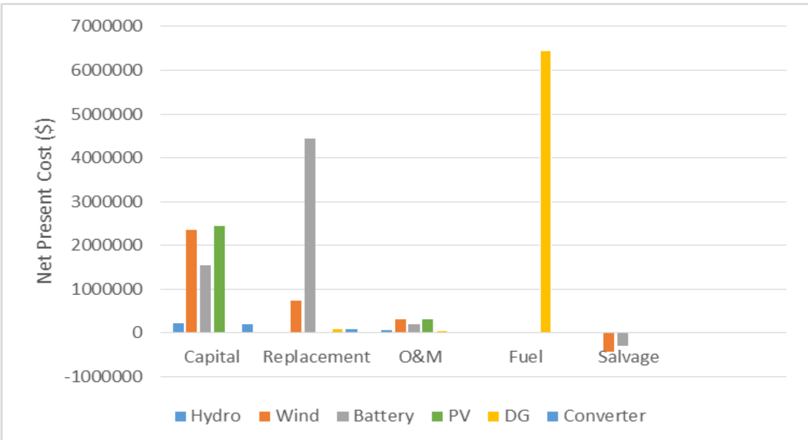

Figure13. Cost Summary of PV/ Wind/Diesel/Hydro/Converter/Battery Configuration

Finally, a detailed comparison of each scenario is conducted. In scenario 1 of PV integration, the net present cost (NPC) amounts to $20.7 million, while the cost of energy is $0.106. On the other hand, in scenario 2 of wind integration, the NPC is $30.4 million while the cost of energy is $0.150. Lastly, in scenario 3 of PV and wind integration, the NPC is $18.8 million and the cost of energy is $0.090. Figure 14 depicts the cost of energy for each scenario on Kadan Island through a bar chart. In Figure 14, scenario 3 has the lowest cost of energy of all scenarios.

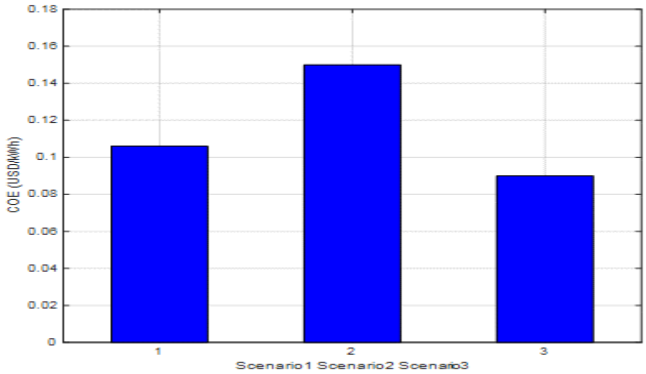

Figure14 . Comparison of the Cost of Energy for Each Scenario

In Figure 15, scenario 2 will significantly decrease the consumption of diesel fuel and reduce the costs associated with operation and maintenance. However, the significant reduction in fuel costs has not been reflected in the COE or NPC due to the expensive investments needed for more wind power, batteries, and converters, as well as its high initial cost.

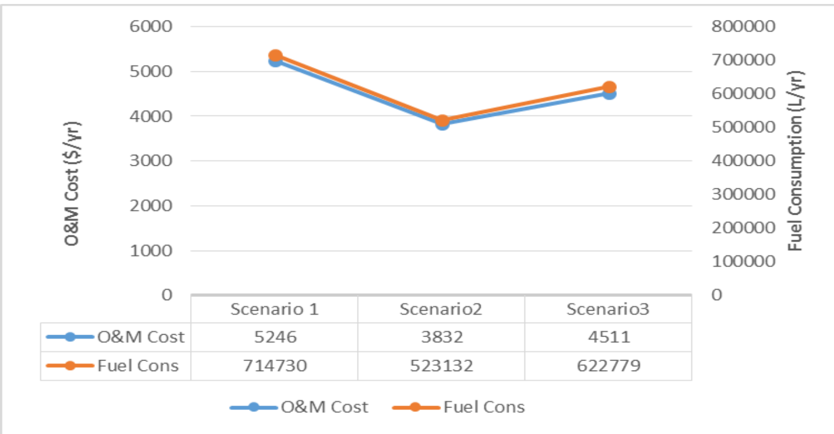

Figure15. Comparison of Fuel with O&M Costs for Each Scenario

In Figure 16, it is obvious that the net present cost decreases from $20.7 million and $30.4 million to $18.8 million, and the cost of energy (COE) decreases from $0.106/kWh and $0.15/kWh to $0.090/kWh. Scenario 3 exhibits the lowest net present cost (NPC) and cost of energy (COE) when compared to scenarios 1 and 2. As a result, customers have the opportunity to acquire electricity at the most affordable rate.

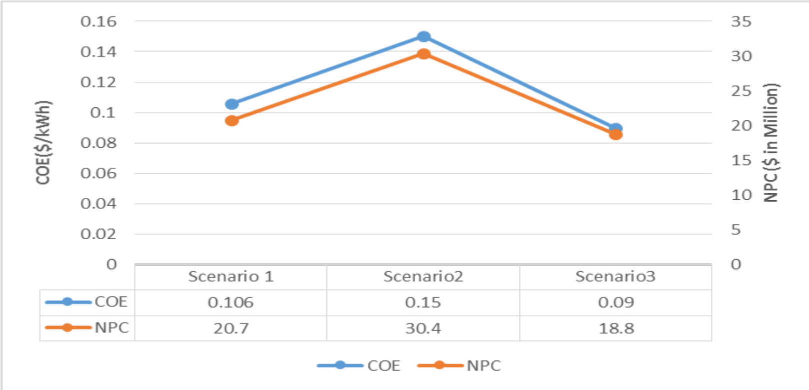

Figure 16. Comparison of COE with NPC for Each Scenario

G. Conclusion

This study focuses on the enhancement of the existing microgrid system on Kadan Island by incorporating various renewable energy sources available in the area. In the existing system, the hydropower plant is unable to function during the summer months. Moreover, diesel generators are predominantly distributed to fulfill the load demand due to the insufficient supply of power from hydroelectric energy. To improve the existing system, three different scenarios were considered, where renewable energy sources were integrated into the existing system. After conducting a comparative analysis of these scenarios, it was recommended to implement scenario 3, which includes PV, wind, hydro, DG, and battery technologies. This particular scenario was found to be the most suitable system for Kadan Island, with the lowest net present cost (NPC) of $18.8 million and a cost of energy (COE) of $0.090 kWh, respectively. Furthermore, scenario 3 stands out as the superior option because it can adequately meet the energy demands of the entire island of Kadan at the lowest cost. For future research, it is suggested to explore different energy storage options, such as compressed air energy storage or a pumped hydro system. This would further enhance the microgrid system's capabilities and reliability.

H. Acknowledgment

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