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Techno-Economic Analysis of Offshore DC Microgrids

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Abstract

Offshore industries depend solely on diesel-based power generation systems or mainland grids, which are expensive and carbon-intensive. The demand for renewable energy-based offshore DC microgrids (MGs) has significantly increased due to rising fuel prices, high costs of fuel transportation and storage, extreme operation and maintenance expenses, and associated carbon emissions. This research study optimises the size of an offshore DC MG that integrates wave, solar, energy storage, and diesel, utilising real-world data from a specific geographical location (latitude −33.525587 and longitude 114.772211), thereby accurately representing the availability of renewable energy sources. An algorithm is designed to optimise the utilisation of highly variable renewable sources via battery-based energy management, resulting in optimal energy dispatch. Utilising economic performance metrics, such as levelised cost of energy (LCoE) and net present value (NPV), this research aims to minimise the energy, operating, and greenhouse gas emission costs while maximising the economic feasibility of the system. A sensitivity analysis is performed to determine the impact of fuel prices, discount rates, and system lifespans on the feasibility of the system. The findings demonstrate that the proposed renewable-based offshore DC MG can substantially reduce fuel consumption (93%), operational expenses (77.56%), and carbon emissions (89.50%) compared with a diesel-only system for offshore platforms, while improving the sustainability and reliability of power supply for aquaculture and marine activities. In addition, the proposed renewable-energy-based offshore DC MG achieves a lower LCoE (0.5649 $/kWh) and a higher NPV ($2.987 \times 10^4$ $) than a conventional diesel-based power generation system for offshore industries. The results provide a decision-making framework for the design and implementation of renewable energy-based offshore DC MGs.

Keywords: hybrid renewable energy systems; offshore DC microgrids; solar photovoltaic; techno-economic optimisation; wave energy

Check for updates

Academic Editor: Seung-Hoon Yoo

Received: 20 March 2026

Revised: 22 April 2026

Accepted: 22 April 2026

Published: 27 April 2026

1. Introduction

Offshore industries, including aquaculture, are transitioning to deep-sea environments as a result of recent technological advancements in offshore engineering, necessitating reliable and sustainable energy solutions [1,2]. These industries rely heavily on diesel-based power generation systems to meet their load demands because of their reliability, simple operation, and low installation costs [3,4]. However, these systems pose significant challenges, including high fuel costs, operating and replacement expenses, and logistical issues related to fuel transportation and storage on offshore platforms, as well as substantial greenhouse gas emissions into marine environments. Therefore, these sectors require reliable and sustainable power generation systems based on local renewable energy sources (RESs), including waves, wind, and solar. Renewable energy-based offshore DC MGs offer cost-effective and reliable alternatives to diesel-based conventional systems, including lower maintenance requirements, reduced fuel consumption, lower carbon emissions, and high efficiency [5].

RES-based DC MGs are not limited to offshore applications; they also offer a viable solution for electrification in isolated and remote areas, including desert, mountainous, and island regions, where conventional grid infrastructure is either inaccessible or economically infeasible. The integration of RESs in offshore DC MGs also supports broader global decarbonisation efforts and renewable energy transition targets. In this context, solar energy remains an important contributor to emission reduction strategies consistent with international climate initiatives, including COP26. However, the installation cost of multiple zero-emission sources on offshore platforms is high, and the integration of multiple RESs suffers from stability issues because of the intermittent nature of these RESs and the highly variable offshore load characteristics [6,7].

Integrating energy storage systems, such as batteries, with multiple stochastic RESs is a viable solution to mitigate the intermittency and to increase the stability of the DC MGs on offshore platforms [8]. In addition, the controller designed for the battery converter maintains overall system stability and improves power quality. However, integrating battery storage increases the capital cost of DC MGs in offshore environments. Recently, the significant reduction in the cost of battery energy storage systems has led to their wider consideration in RES-based DC MG systems [9]. Therefore, an offshore DC MG system requires a cost-effective solution, which includes battery optimisation and an effective energy management strategy [10]. To address these challenges, this research study focuses on the detailed techno-economic evaluation of offshore DC MGs and the development of an algorithm for a comprehensive energy management system that incorporates economic operation strategies and optimal system sizing.

Stochastic renewable energy-based MGs have been the subject of a significant number of research articles over the last decades, primarily focusing on island and terrestrial contexts. For instance, PV–diesel, PV–battery, and PV–diesel–battery configurations are widely considered for conducting research to enhance techno-economic performance [11–14]. In [15], a new LCoE-based metric was proposed for the techno-economic evaluation of a PV–battery system. In addition, PV–wind, PV–wind–battery, PV–wind–diesel, and PV–wind–battery–diesel configurations have been studied to minimise operational expenses and carbon emissions [16–20]. Nonetheless, these MGs are not specifically designed for offshore industries that employ local RESs. In addition, all previous research has mostly concentrated on AC MGs.

On the other hand, DC MGs have attained significant attention for offshore environments, offering lower costs due to a smaller number of conversions, simplified control systems, and improved compatibility with RESs and battery storage systems [21,22]. Moreover, numerous studies have employed the Hybrid Optimisation of Multiple Energy Resources (HOMER) software tool for techno-economic analysis. However, such studies often rely on simplified component models and therefore may not fully capture the holistic optimisation of offshore DC MG architecture and operation. Such an approach could potentially diminish reliability for complex systems with high-resolution real offshore generation and load characteristics [23,24]. A sequential quadratic programming method is a prominent, extensively utilised, and effective solution for optimising MGs under nonlinear constraints [25].

https://doi.org/10.3390/en19092108

In MG studies, especially those designed for offshore platforms, wave energy is one of the most promising sustainable and consistent renewable resources compared with solar and wind energy due to its high power density [26]. This sort of energy is more forecastable than wind and solar energy and can be used during the nighttime, unlike solar energy [27]. Although wave energy has enormous potential, it has received inadequate attention in the design of DC MG systems in offshore platform applications. A feasibility study on the techno-economic analysis and potential of wave power generation is described in [28,29], focusing on essential performance measures such as the LCoE and the NPV. A hybrid arrangement, incorporating both wave and solar energy, is evaluated for power generation in [30], where a techno-economic feasibility analysis is conducted at three sites in Iran. However, a comprehensive design of MGs in offshore environments with specific load considerations is missing, necessitating more extensive research on wave-based DC MGs, particularly in relation to offshore load profiles.

Until now, limited research studies have been conducted in the design of offshore DC MGs, emphasising primarily wave energy sources, without addressing system-level aspects, such as energy management, load balancing, cost analysis, and environmental considerations. This lack of research indicates the need for a comprehensive techno-economic analysis that emphasises not only wave-based generation but also load-generation balancing, offshore load dynamics, system optimisation, and associated cost considerations. Accordingly, the purpose of this study is to develop and evaluate a techno-economic optimisation framework for offshore DC MGs using realistic offshore load and renewable resource data. The main objectives are to determine an optimal system configuration, assess system performance under normal and adverse operating conditions, and compare the proposed renewable-based solution with a conventional diesel-based supply system in terms of cost, fuel consumption, and emissions.

This analysis incorporates high-resolution real-world data, including significant wave height and periods, solar irradiance, and temperature from a single location, alongside actual aquaculture load profiles, thereby providing an accurate assessment of the performance of the proposed DC MGs for offshore industries. A cost-effective energy management strategy is developed to ensure effective power balancing between supply and demand, considering system optimisation and associated costs through MATLAB/Simulink R2024a. The techno-economic analysis is conducted through LCoE and NPV, quantifying the effectiveness of the proposed DC MG system for offshore environments. In addition, a sensitivity analysis is also carried out to assess the impact of fuel costs, discount rates, and system lifetimes. The key contributions of this research are summarised as follows:

(1) This research study optimises the sizes of wave, solar, battery, and diesel units used in a DC MG for offshore industries, with wave energy uniquely emphasised as a primary source.
(2) This analysis utilises real-world wave and solar power generation profiles from a specific geographical location (latitude −33.525587 and longitude 114.772211), incorporating real aquaculture load profiles, thereby providing practical insights into the operational feasibility of RESs in offshore environments.
(3) A novel energy management strategy is developed to ensure the balancing of supply and demand, considering system optimisation, operating costs, and environmental aspects.
(4) This study performs a sensitivity analysis to assess the impact of fuel costs, discount rates, and system lifespans, establishing a decision-making framework for offshore industries.

The subsequent sections of the paper are structured as follows: Section 2 initially presents a generic description of an offshore DC MG network, integrating wave, solar, battery, and diesel to deliver power to aquaculture, including real generation and load

https://doi.org/10.3390/en19092108

profiles. Section 3 outlines the methodology for the system optimisation and the technical, economic, environmental, and sensitivity analyses of the proposed offshore DC MG configuration. Section 4 discusses simulation results, featuring realistic case studies. Section 5 finally summarises the key findings of the paper.

2. Modelling of DC Microgrids in Offshore Platforms

A DC MG network for offshore applications based on local RESs such as wave and solar energy is shown in Figure 1. In this analysis, wave and PV are considered to develop DC MG systems for offshore applications because of their suitability and complementary attributes. Although wind energy is another viable option, it is not considered to maintain a focused offshore system configuration and reduce system complexity, which is crucial for ensuring efficient energy management and operational reliability in offshore environments. However, the proposed design is flexible and can be extended to integrate additional renewable energy sources, including wind, based on site-specific requirements. Implementing local RESs for offshore DC MG systems without grid connectivity presents a technically and economically viable solution by avoiding expensive transmission lines, improving local energy efficiency and reliability, lowering electricity expenses, fostering economic development, and aiding in emission reduction. This system is designed to deliver power to aquaculture loads. To mitigate the intermittent nature of stochastic RESs, a battery storage system is integrated with the MG network, ensuring reliable and stable power for these critical offshore loads. In addition, a diesel generator is connected to serve in emergency situations when both wave and solar sources are unable to meet the load demand, and the battery is fully discharged. The proposed methodology—including resource modelling, system configuration, optimisation, and sensitivity analysis—is inherently scalable and can be extended to larger offshore installations by appropriately adjusting system capacity, component sizing, and operational constraints. Moreover, the framework can be adapted to accommodate integration with existing offshore infrastructure by incorporating the relevant electrical interface requirements, load characteristics, and operational considerations into the system design and optimisation process.

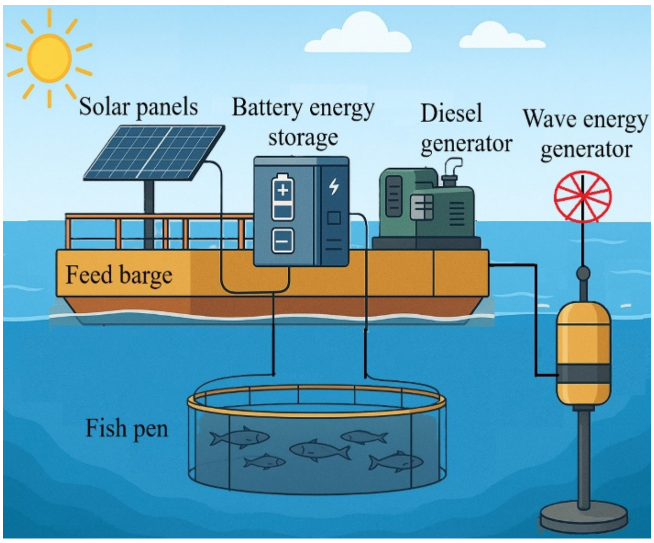

Figure 1. A typical DC MG network on offshore platforms.

2.1. System Description

A detailed schematic diagram of the proposed offshore DC MG for aquaculture is presented in Figure 2, consisting of a wave energy converter (WEC), solar panels, battery systems, a diesel generator, offshore loads, and a dump load. An Archimedes Wave Swingbased WEC is connected to a permanent magnet linear generator to convert wave power into electricity. The power generated from waves is normally AC, requiring a rectification process to convert it into DC power. A DC-DC power conversion stage is designed to inject this power into the DC bus through a maximum power point tracking algorithm (MPPT), ensuring energy efficiency and stable operation. In contrast, solar energy generates DC power that can be injected directly into the DC bus through a DC-DC conversion stage controlled by an MPPT algorithm. While RES-based offshore DC MGs improve environmental outcomes, they can pose significant challenges in maintaining stability due to the extremely unpredictable nature of offshore generation and highly variable load profiles. Incorporating a battery system provides a feasible and effective solution to address this issue by guaranteeing a reliable, balanced, and uninterruptible power supply for these critical loads. This battery system interfaces with the DC bus via a bidirectional DC-DC conversion stage, incorporating a robust control system to regulate the DC bus voltage and thereby maintaining system stability during fluctuating generation and load conditions.

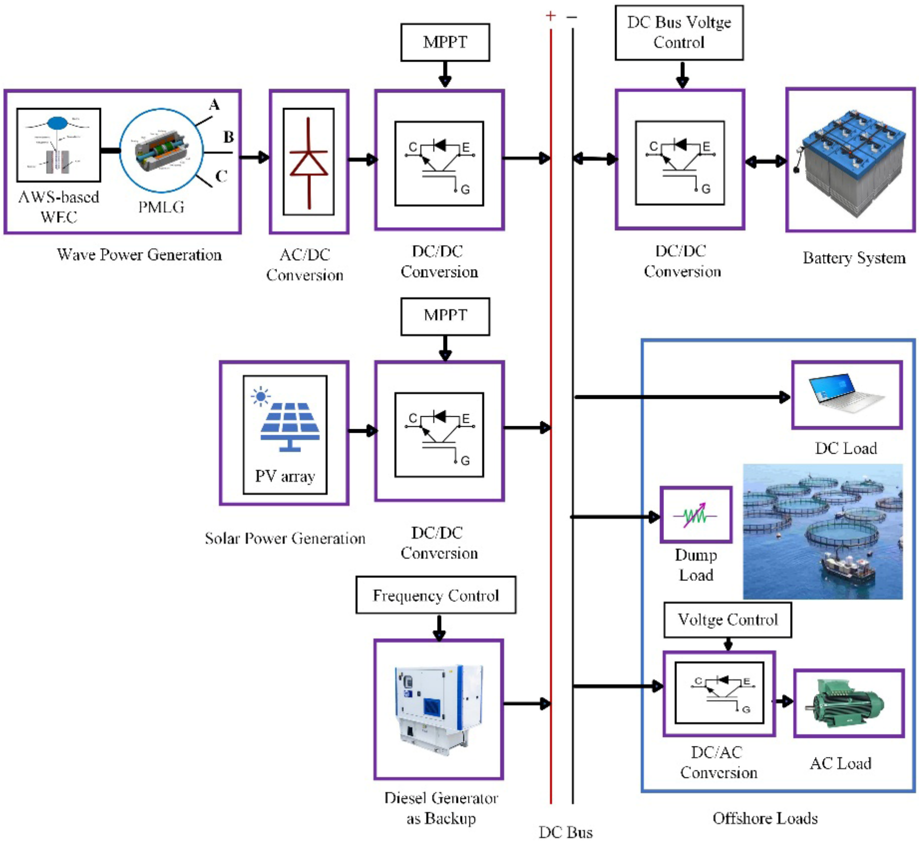

Figure 2. A schematic of the proposed offshore DC MG network for aquaculture.

Although diesel generators are a major concern due to emissions and operating costs, they cannot be completely removed from the system, especially for critical loads. For example, in rare cases when there are no waves and no sun for a few consecutive days, the battery may become fully discharged. Two options may be considered: one is load shedding based on priorities, and another is to run a diesel generator as a backup source.

The DC MG designed for offshore industries can supply power to both DC and AC loads. A DC-AC conversion stage is required for connecting AC loads to the system. In addition, a dump load, a set of dynamic variable load resistors, is connected to the network and acts as a regulator. This load consumes power when generation exceeds the load demand and the battery is fully charged, balancing generation and load.

2.2. Site Description

This research study utilises real data, including significant wave height, wave periods, solar irradiance, and temperature, collected from a specific geographical location (latitude −33.525587 and longitude 114.772211). This location is off Cape Naturaliste, in south-western Western Australia (WA), approximately 25 km away from the coastline of WA, as shown in Figure 3. The Department of Transport of WA has installed this wave monitoring system at a 50 m water depth. In addition, the solar irradiance and temperature profiles are also collected from the same location through the National Solar Radiation Database. The present study focuses on a single offshore location, selected primarily because high-quality, publicly accessible measured wave data are available from an operational wave monitoring system. For many offshore regions, access to reliable wave profiles with sufficient temporal resolution remains limited, in contrast to solar irradiance data, which are widely available through established databases. Therefore, while the numerical results reported here are site-specific, the proposed optimisation framework itself is readily applicable to other locations where suitable input data are available.

Figure 3. The location of the study area for generating wave and solar profiles.

2.3. Wave Power Generation Profile

The energy derived from ocean waves can be determined using the significant wave height and wave periods, as expressed in (1).

$$P_{wave} = \frac{\rho g^2 T_w H_w^2}{32\pi} \quad (1)$$

where P_{wave} represents the wave power per unit length (W/m), ρ denotes the density of seawater (≈1025 kg/m^3), g signifies the acceleration due to gravity (m/s^2), T_w indicates the wave periods (s), and H_w refers to the significant wave height (m). The collected significant wave height (H_w) and wave periods (T_w) from the Cape Naturaliste wave monitoring system are shown in Figure 4.

It is evident from the yearly data that wave height varies significantly over time, from 0.7 m to 7.38 m. The wave periods also fluctuate substantially with respect to time, from 3.85 s to 13.35 s. The wave height and periods are comparatively higher in the winter season than in the summer season. The electrical output of a WEC can be calculated using the wave energy expressed in (2).

$$P_{elec} = P_{wave} \times L_{wc} \times \eta_w \quad (2)$$

In this context, P_{elec} represents the electrical power derived from wave energy in kW, L_{wc} indicates the effective length of the converter in m, and η_w denotes the conversion efficiency. This electrical power is also called the 'uncapped electrical power', and a fixed size of WEC is required to extract the actual electrical power from the wave energy. The actual capped electrical output power can be obtained using the following formula, as stated in (3).

$$P_{elec}(actual) = \min(P_{elec},\ P_{rated}) \tag{3}$$

where P_{rated} represents the rated capacity of the WEC in kW. The dimensions of the WEC can be determined through a comprehensive analysis of load requirements, considering the LCoE and the curtailment of wave power.

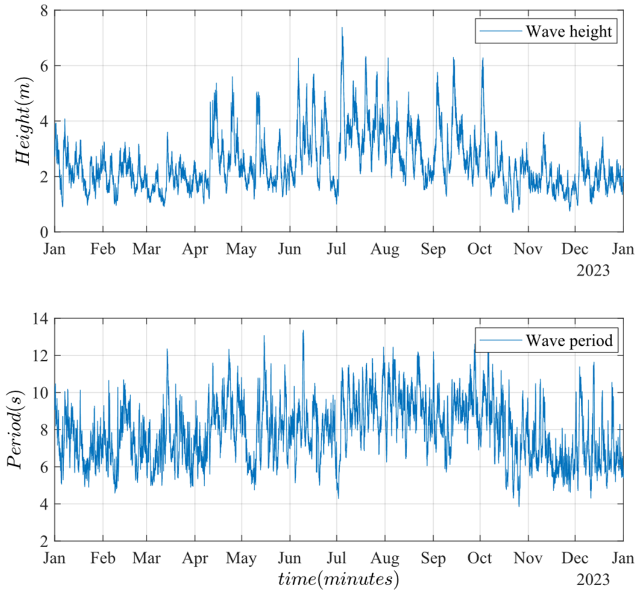

Figure 4. Wave height and periods at Cape Naturaliste in 2023.

2.4. Solar Power Generation Profile

The output profile of PV generation varies with respect to time due to the changes in effective solar irradiance, weather conditions, and location. The effective solar irradiance and temperature profiles are collected from the same location as the wave profile, as shown in Figure 5. The annual profile indicates that solar irradiance varies considerably, ranging from 0 W/m^2 to 1046 W/m^2. The temperature varies throughout time, from 13 °C to 28 °C. Solar irradiation and temperature are significantly elevated during the summer compared to the winter.

The solar panel's output power can be determined using the solar irradiation and temperature as described in (4).

$$P_{pv} = I_{solar} \times A_{solar} \times \eta_s \times T_{eff} \tag{4}$$

where P_{pv} signifies the solar power generation (kW), I_{solar} indicates the effective solar irradiance (W/m^2), A_{solar} represents the effective area of the solar panel (m^2), η_s denotes the efficiency of the solar system, and T_{eff} refers to the effective temperature coefficient. The coefficient of temperature is calculated by the following formula:

$$T_{eff} = 1 + k_T\left(T_{pv} - T_0\right) \tag{5}$$

where k_T, T_{pv}, and T_0 are the temperature coefficient, temperature of the solar panel, and nominal temperature, respectively.

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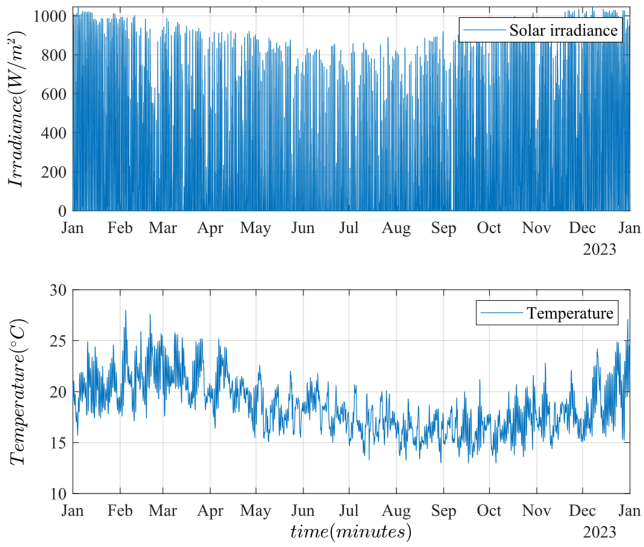

Figure 5. Solar irradiance and temperature at Cape Naturaliste in 2023.

2.5. Load Profile

In this research study, a load profile is collected from an aquaculture facility to conduct techno-economic analysis, as shown in Figure 6. The offshore load fluctuates highly over time, and load demand varies from 2.7 kW to 56.5 kW. The offshore load can be divided into two categories, summer season load demand and winter season load demand, as presented in Figure 7.

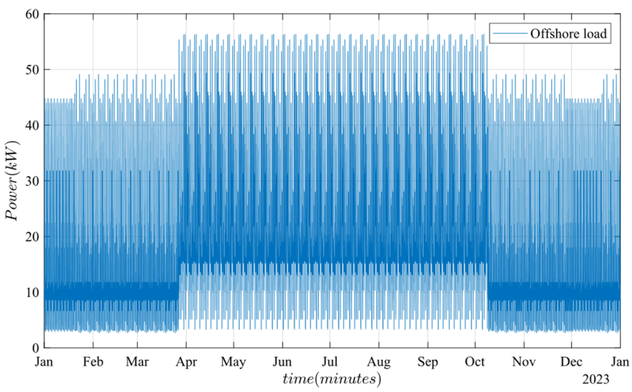

Figure 6. Yearly load profile of aquaculture.

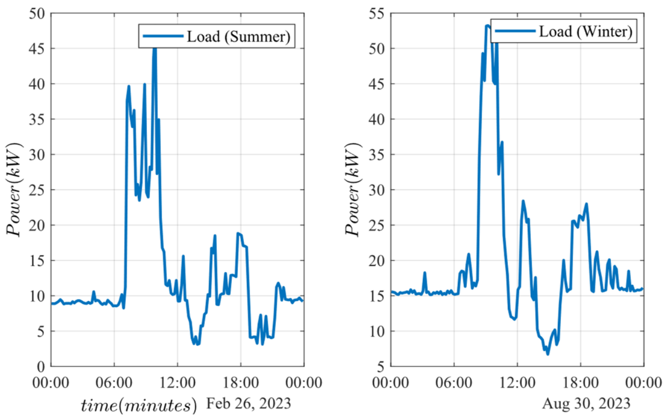

Figure 7. Daily load profile of aquaculture.

The average load is found to be around 22 kW during the summer season and approximately 28 kW in the winter season. The load demand is comparatively higher in the winter season than in the summer season. In the winter season, fish farms require additional lighting loads because of shorter daylight hours. The daily load curve clearly shows that peak demand occurs two or three times, corresponding to feeding times that may vary based on the sizes of the fish. In general, feeding processes occur approximately from 7:00 am to 10:00 am, 12:00 pm to 2:00 pm and 5:00 pm to 7:00 pm. The load demand remains almost constant during the nighttime because there is no feeding demand at night.

3. Techno-Economic Analysis of Offshore DC MGs

This section outlines the necessary details of the technical, economic, environmental, and sensitivity analysis for assessing the feasibility of DC MGs on offshore platforms. The performance of the DC MG in the offshore environment is analysed based on system optimisation, power balancing between generation and load demand, a control strategy for energy management, operating expenses, LCoE, net present cost (NPC), NPV, and carbon costs. In addition, a detailed sensitivity analysis is conducted to assess how fuel costs, discount rates, and system lifespans influence the overall performance of DC MG systems.

3.1. Optimal Sizing of Offshore DC MGs

The proposed offshore DC MG is optimised using a sequential quadratic programming function that incorporates multi-start nonlinear constraints. This algorithm optimises system parameters based on available load profiles and optimal utilisation of wave and solar resources, while evaluating LCoE, NPC, NPV, and carbon emissions. The system size can be characterised using the design vector presented in (6).

$$x = [x_1,\ x_2, x_3, x_4] \tag{6}$$

where x_1 represents the capacity of the WEC in kW, x_2 indicates the capacity of the solar unit in kW, x_3 denotes the capacity of the battery in kWh, and x_4 symbolises the capacity of the diesel generator in kW. The variable x is optimised, considering NPC as the objective function, while LCoE and NPV are used as techno-economic evaluation metrics, together with the additional constraints of the proposed offshore DC MG. Each unit's dimensions must adhere to the specified restrictions outlined in (7)–(10).

$$0 \le x_1 \le x_1^{max} \tag{7}$$

$$0 \le x_2 \le x_2^{max} \tag{8}$$

$$0 \le x_3 \le x_3^{max} \tag{9}$$

$$0 \le x_4 \le x_4^{max} \tag{10}$$

Each unit of the proposed offshore DC MG is optimised to ensure that the system operates reliably, effectively, efficiently, and economically, considering the following constraints:

(1) Reliability: In this analysis, the system is capable of fulfilling the total load demand at any time, indicating zero unserved load.

$$P_{load}(unserved) = 0\ ,\ \forall t \tag{11}$$

(2) Diesel generator: The diesel generator can supply the full plant load to tackle any emergency situations.

$$x_4 \ge P_{load}^{max} \tag{12}$$

(3) PV unit: A solar unit is proposed for installation on the accessible roof area of the feed barge in this offshore DC MG system for aquaculture. The solar unit can be constrained using the formula provided in (13), based on the available roof area.

$$x_2 \leq \frac{A_{roof} \times S_d \times f_s}{1000} \tag{13}$$

where

A_{roof} = Available area in m^2.
S_d = Solar density in W/m^2.
f_s = Solar layout derate factor.

(4) Objective function: The dimensions of the design variables are optimised using the sequential quadratic programming function (*fmincon*), which is constrained by specified lower and upper bounds, as detailed in (7)–(10), respectively. The dimensions of these parameters are autonomously optimised to minimise the objective function while adhering to all restrictions, including reliability, optimal use of RESs, and reduced fuel dependency. The objective function, NPC, is articulated as in (14), representing the summation of capital cost (C_{cap}), operational and maintenance expenses ($C_{O\&M}$), and fuel-related costs (C_{fuel}). This optimisation approach identifies the optimal combination of the WEC, PV, battery, and diesel generator sizes via an iterative process. For each iteration, this algorithm evaluates the system by utilising available load and generation profiles, an energy dispatch strategy, an objective function, and battery charging and discharging parameters.

$$f(NPC) = \min\left(\sum C_{cap} + C_{O\&M} + C_{fuel}\right) \tag{14}$$

3.2. Technical Analysis

The battery storage unit is an essential element of RES-based DC MG systems because this unit can mitigate the intermittent nature of wave and solar sources. This system can balance the power between the generation and load demand through charging and discharging processes. It absorbs power from the system when generation exceeds the load demand. Similarly, when load demand exceeds the generation, it releases power to the system, ensuring balance and a reliable power supply. The operation of a battery storage unit relies on the availability of local wave and solar energy, state of charge (SoC) and discharge constraints, and depth of discharge (DoD). Consequently, this unit must function within the manufacturer-defined permissible limitations of SoC and DoD as articulated in (15) and (16), respectively.

$$SoC_{min}(t) \leq SoC(t) \leq SoC_{max}(t) \tag{15}$$

$$SoC_{min}(t) = (1 - DoD) \times SoC_{max}(t) \tag{16}$$

The power generated from multiple sources and interconnected loads must be balanced to maintain stable operation of the system, and the power balancing equation can be expressed in (17) as follows:

$$\sum_{i=1}^{N_{load}} P_{Load}(i,t) = \sum_{j=1}^{N_{WEC}} P_{wave}(j,t) + \sum_{k=1}^{N_{pv}} P_{pv}(k,t) - \sum_{l=1}^{N_{bat}} P_{bat}^{ch}(l,t) + \sum_{m=1}^{N_{bat}} P_{bat}^{dis}(m,t) + \sum_{n=1}^{N_{DG}} P_{DG}(n,t) - \sum_{x=1}^{N_{DL}} P_{DL}(x,t) \tag{17}$$

where P_{load} (i, t) represents the total connected loads, P_{wave} (j, t) denotes the total electrical power generated by the WEC, P_{pv} (k, t) signifies the total solar power generation, P_{bat}^{ch} (l, t) indicates the battery charging power, P_{bat}^{dis} (m, t) denotes the battery discharging power,

P_{DG} (n, t) presents the diesel generation, and P_{DL} (x, t) represents to the power consumed by the dump loads.

A system-level control system is required to balance generation and load demand, ensuring minimum operational costs and maximum use of RESs. A cost-effective energy dispatch system is developed to balance the system, considering battery storage systems, diesel generators, and dump loads, as shown in Figure 8. The priority of energy dispatch depends on the net power, which is the difference between total generation from RESs and total connected loads, and can be expressed in (18).

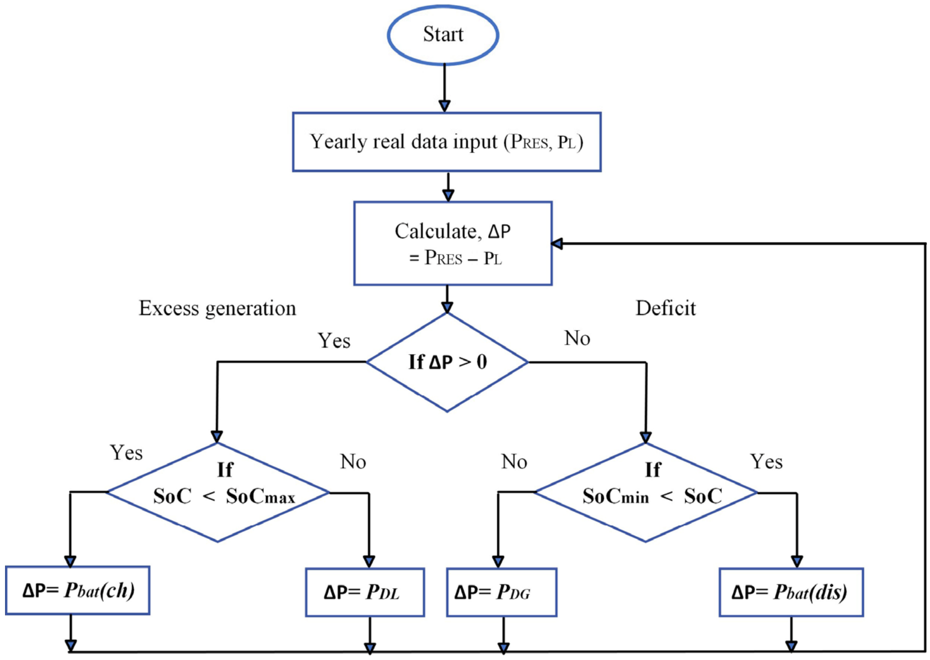

Figure 8. Flowchart of energy dispatch algorithm.

$$\Delta P\ (t) = P_{RES}(t) - P_{load}(t) \tag{18}$$

(i) If ΔP > 0, the total generation (P_{RES}) from RESs exceeds the total connected loads (P_{load}), initiating the charging of the battery. When the battery reaches its operational limit $(SoC(t) \leq SoC_{max}(t))$, a dump load ($P_{DL}$) is connected to release the excess power and maintain balanced operation.

(ii) If ΔP < 0, the entire generation (P_{RES}) from RESs is inadequate to satisfy the load demand (P_{load}), necessitating battery discharge to fulfil the requirement. A diesel generator (P_{DG}) is activated when the battery discharge reaches its minimum threshold $(SoC_{min}(t) \leq SoC(t))$, ensuring balance between power generation and load demand.

3.3. Economic Analysis

The economic performance of DC MG systems can be characterised through LCoE and NPV. A lower LCoE and a higher NPV indicate the most cost-effective solution, ensuring optimal use of RESs and minimum costs of electricity production. The LCoE can be calculated using the following Equation (19).

$$LCoE = \frac{C_{cap}\left[\frac{d(1+d)^n}{(1+d)^n-1}\right] + C_{O\&M} + C_{fuel}}{E_{anual}} \tag{19}$$

In this equation, C_{cap} represents the capital costs ($), $C_{O\&M}$ denotes the annual operation and maintenance costs ($), C_{fuel} signifies the yearly fuel costs ($), E_{annual} indicates the annual power delivered (kWh/year), d is the discount rate, and n represents the system's useful life (year). The value of LCoE heavily relies on capital and fuel costs. The LCoE in this study is calculated based on direct economic cost components, including capital, replacement, O&M, and fuel costs. A separate CO_2 cost term is not included in the formulation, as no explicit carbon-pricing policy or emissions charge is assumed. The environmental effect of the system is instead evaluated separately through the carbon emissions analysis. This study aims to minimise the value of LCoE, indicating a low electricity cost per unit of generation.

The NPV is another key metric to measure the economic feasibility of DC MG networks and can be expressed in (20) as follows:

$$NPV = (B - C)\left[\frac{(1+d)^n - 1}{d(1+d)^n}\right] + \frac{S}{(1+d)^n} - C_{cap} \tag{20}$$

In this context, B, C, and S represent the annual benefits ($), annual operating costs ($), and annual salvage value ($), respectively. Table 1 summarises the economic specifications of the system components corresponding to different cost categories derived from current literature sources [5,20,28]. The parameters used in this analysis were selected based on a comparative review of reported values in the literature and prevailing market conditions.

Table 1. Technical and economical parameters [5,20,28].

Parameters	Value			
	Wave	**PV**	**Battery**	**Diesel**
Capital cost	14,000 $/kW	1000 $/kW	700 $/kWh	600 $/kW
O&M costs	3% of Capex	10 $/kW/year	10 $/kWh/year	0.01258 $/kWh
Replacement cost	8000 $/kW	800 $/kW	500 $/kWh	450 $/kW

3.4. Environmental Analysis

Diesel-based power generation contributes a significant amount of carbon to the environment, which is a major concern for maintaining sustainability. The costs of emissions depend solely on the use of diesel in the DC MG systems. The proposed offshore DC MG networks for aquaculture offer lower emissions, reflecting lower carbon costs. The aim of this configuration is to optimally use RESs with battery systems, and diesel is only used in emergency situations. The carbon emission ($C_{emission}$) costs can be expressed as follows in (21):

$$C_{emission} = \sum_{t=1}^{t=N} E_{DG}(t) \times k_{SFC} \times k_{EF} \times C_{price}/1000 \tag{21}$$

where $E_{DG}(t)$ represents the total energy produced by the diesel generator in kWh, k_{SFC} denotes the specific fuel consumption rate in L/kWh, k_{EF} signifies the emission factor in kg/L, and C_{price} indicates the carbon price per ton.

3.5. Sensitivity Analysis

In this research study, a sensitivity analysis is conducted to examine the influence of fuel costs, discount rates, and lifespan on the operation of the DC MG systems in offshore platforms. A slight variation in these parameters can impact the system's LCoE and NPV. For example, the fuel price depends on the international political conditions, and it can significantly impact energy generation. Thus, these parameters are highly sensitive to offshore DC MG operation. The sensitivity of the DC MGs due to fuel costs, discount rates, and project lifespan can be characterised as follows:

$$\Delta S_{fuel} = \frac{\%\Delta LCoE}{\%\Delta C_{fuel}} \tag{22}$$

$$\Delta S_{d} = \frac{\%\Delta LCoE}{\%\Delta d} \tag{23}$$

$$\Delta S_{n} = \frac{\%\Delta LCoE}{\%\Delta n} \tag{24}$$

4. Results and Discussion

The techno-economic evaluation of the proposed offshore DC MG network is conducted using MATLAB R2024a software with a 10 min resolution of generation and load profiles. In this study, the peak load of the given aquaculture facility is 56.5 kW. Based on the available load characteristics and defined constraints, the developed algorithm optimises each unit of the offshore DC MG, considering the optimal use of wave and solar resources, with NPC as the objective function, while LCoE, NPV, and carbon emissions are used as evaluation metrics. Table 2 shows the optimised results for the system. The optimal offshore DC MG system comprises a 29.60 kW WEC, an 18 kW solar unit, an 83.78 kWh battery system, and a 56.5 kW diesel generator. In addition, the achieved optimised system has an LCoE of 0.5649 $/kWh, an NPC of 84,462 $/year, a renewable fraction of 88.29%, and an annual diesel energy of 17.51 MWh/year. To validate the effectiveness of the designed algorithm for system optimisation, the system is reoptimised based on 10% incremental and decremental fuel prices, as presented in Table 2.

Table 2. Optimised results of the offshore DC MG system.

Parameters	Optimised Results		
	Constant Fuel Price	10% Increase in Fuel Price	10% Decrease in Fuel Price
Wave (kW)	29.60	30.67	28.76
Solar (kW)	18	18	18
Battery (kWh)	83.78	88.31	77.77
Diesel (kW)	56.5	56.5	56.5
LCoE ($/kWh)	0.5649	0.5662	0.5649
NPC ($/year)	84,462	84,701	84,452
Annual diesel energy (MWh/year)	17.51	16.44	18.53

4.1. Impact of Battery Size in Offshore DC MGs

The battery is the key component in the offshore DC MG networks, and directly impacts the use of diesel when RES-based generation is not sufficient to meet the highly variable offshore load demand.

The battery charge limit, discharge limit, and battery round trip efficiency are considered at 95%, 10%, and 95%, respectively. The capacity of the battery directly influences operating costs ($/kWh), LCoE ($/kWh), annual diesel (L/year), annual carbon emissions (tons), annual wasted energy (MWh), and the percentage of diesel and battery contributions, as presented in Table 3.

https://doi.org/10.3390/en19092108

Table 3. Battery size mapping.

Parameters	Battery Capacity (kWh)			
	50	**100**	**200**	**400**
Operating cost ($/kWh)	0.203	0.193	0.187	0.185
LCoE ($/kWh)	0.5517	0.5649	0.6073	0.7008
Annual diesel (L)	7270	6282	5412	4293
Annual carbon (tons)	18.46	15.95	13.74	10.9
Annual wasted energy (dumped load) (MWh)	8.12	7.69	7.3	6.8

This analysis demonstrates that an increased battery capacity reduces operational costs, diesel use, carbon emissions, and energy waste. Nonetheless, an increase in battery size elevates the LCoE. It is evident that beyond the optimal battery capacity, each incremental increase in battery capacity yields diminishing returns in fuel consumption, while the LCoE steadily escalates. Consequently, augmenting the battery capacity is not economically warranted unless a particular carbon emission limitation exists.

4.2. Performance Comparison with Diesel-Only Offshore DC Microgrids

Figure 9 presents the wave and solar power generation profiles from the same geographical location, along with the offshore load profile from an aquaculture facility. The power generated from both wave and solar energy, as well as the offshore loads, fluctuates significantly over time. The wave power output varies from 0.8759 kW to 30 kW, whereas the solar output changes from 0 kW to 18.7370 kW. A battery system is a viable solution to address this intermittency, and a cost-effective energy management system is developed to optimise the use of RESs and battery, and to minimise the operating costs and carbon emissions. The battery SoC, charging and discharging energy, required diesel generation, and power consumed by the dumped load are shown in Figure 10. The proposed energy management system effectively balances generation and load demand, minimising operating costs and carbon emissions. To balance the power, the battery system annually absorbs approximately 1.98×10^4 kWh of energy and discharges energy to the load subject to the battery round-trip efficiency.

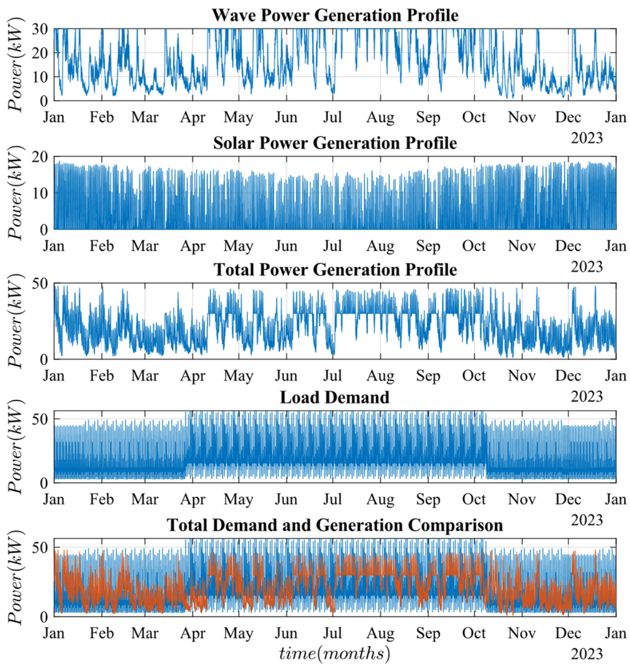

Figure 9. Yearly generation and load profiles.

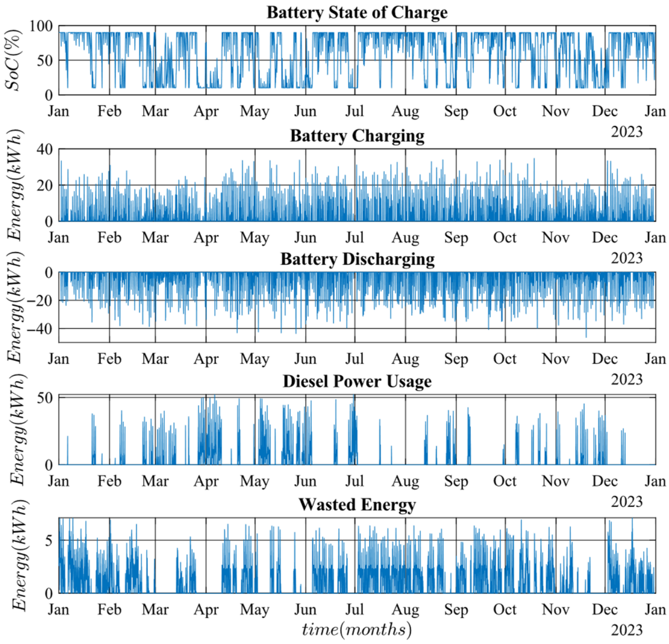

Figure 10. Yearly battery responses, diesel generation and power consumption by the dump load.

When the total generation is unable to fulfil the load demand and the battery is fully discharged, the diesel generator is activated to run the plant without any power outages or interruptions. To deliver power in this situation, the diesel generator generates 1.0732×10^4 kWh of energy annually. Similarly, when the load demand is lower than generation and the battery is fully charged, an additional dump load consumes 6.8181×10^3 kWh of excess energy yearly to maintain the balance condition between the generation and load demand.

The techno-economic effectiveness of the proposed RES-based offshore DC MGs is compared with diesel-only offshore DC MGs, considering different performance parameters, including operating expenses, carbon emissions, LCoE, NPV, NPC, and the percentage of each generation. Table 4 summarises the comparisons between these two systems. The RES-based offshore DC MG system significantly outperforms the conventional diesel-based system across all key performance indicators. In particular, the proposed configuration demonstrates substantial reductions in operating cost, carbon emissions, LCoE, and total system cost, confirming both its economic and environmental advantages for offshore applications. These results indicate that integrating renewable energy sources can significantly reduce diesel dependency while improving the overall sustainability and cost-effectiveness of offshore power supply systems.

Table 4. Techno-economic performance comparison with diesel-based system.

Parameters	Type of Offshore DC MGs	
	Diesel-Based	RES-Based
Operating costs ($/kWh)	0.86	0.193
Annual carbon emission (tons)	151.90	15.95
LCoE ($/kWh)	0.8850	0.5649
NPV ($)	-9.12×10^5	2.987×10^4
NPC ($/year)	1.79×10^5	8.44×10^4

It is evident from the summary that RES-based offshore DC MG systems significantly reduce the operating expenses, diesel dependency, environmental impacts, NPC, and cost of electricity and increase the NPV over the project lifetime. In the proposed configuration, wave contributes 70%, solar contributes 16%, and diesel supplies 7% of the total energy demand, and the battery supports short-term balancing through charge/discharge operation.

4.3. Case Studies

In this study, uncertainty is addressed through the use of real time-series load and renewable-generation profiles, which capture temporal variability, together with scenario-based analysis under adverse operating conditions, including short-term and extended unavailability of wave and solar resources. In addition, sensitivity analyses on key economic parameters are conducted to examine the robustness of the techno-economic results. While a formal probabilistic uncertainty analysis is beyond the scope of the present work, these deterministic and scenario-based assessments provide useful insight into system performance under variable operating conditions. The outage scenarios were selected from the analysed time-series data to represent critical operating conditions, including both short-term renewable fluctuations and prolonged low-generation periods. Short-duration cases reflect typical intra-day variability, whereas extended outage cases represent more severe conditions involving sequential or simultaneous unavailability of wave and solar resources. These scenarios were chosen to enable a meaningful assessment of system resilience and operational robustness under realistic and adverse offshore operating conditions.

4.3.1. Case Study I

Assume that the weather conditions on 3 March 2023, from 9 am to 12 pm and 12 pm to 3 pm, respectively, result in zero wave and solar power generation, as illustrated in Figure 11. The generation and load profiles indicate that the battery is in a discharge condition before 9 am, and the diesel generator provides additional power when wave power is unavailable. Similarly, when solar power is zero, additional power comes from the diesel generator, as wave power is not sufficient to fulfil the load demand from 12 pm to 3 pm.

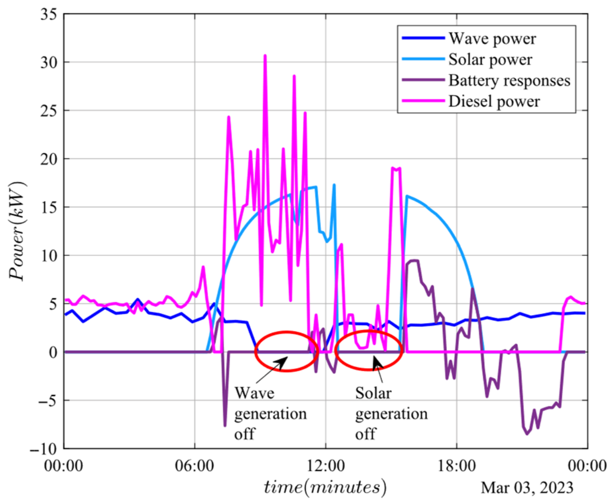

Figure 11. Unavailable wave and solar power for three hours.

4.3.2. Case Study II

This scenario contemplates a catastrophic and adverse situation, characterised by the successive unavailability of wave and solar energy generation over several days, from

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11 July to 15 July 2023. Initially, no wave power is available from 11 July to 13 July 2023, followed by a lack of solar power from 13 July to 15 July 2023, as illustrated in Figure 12.

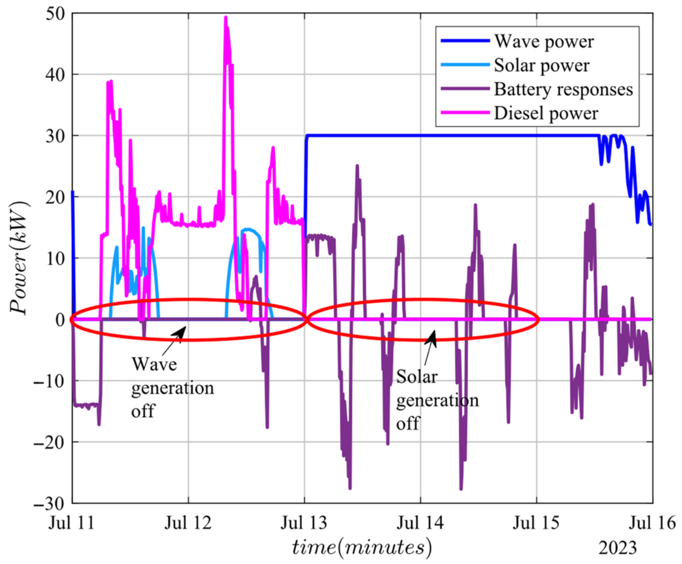

Figure 12. Unavailable wave and solar power for four consecutive days.

The diesel generator is used in the absence of wave power, as solar energy alone is insufficient to meet the load demand. In the absence of solar power, wave power sufficiently meets the load requirement, indicating that diesel power is unnecessary.

4.3.3. Case Study III

This analysis considers the simultaneous unavailability of wave and solar power from 11 July to 13 July 2023, as illustrated in Figure 13. Analysis of the generation and load profiles indicates that when wave and solar energy sources are not available, the battery retains sufficient power to meet the load demands. When the battery is fully discharged and power generation from wave and solar sources is absent, diesel is activated to fulfil the load demand.

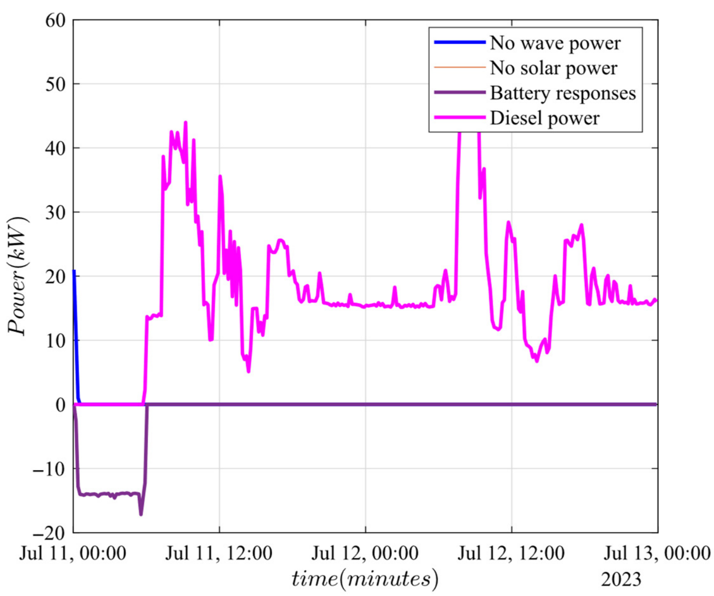

Figure 13. Unavailable wave and solar power simultaneously.

The performance metrics, including operating expenses, fuel price, carbon emissions, LCoE, and NPV, of the proposed offshore DC MG systems are recalculated, considering critical case studies. Table 5 outlines the effectiveness of the proposed system, showing a negligible increase in operating costs of 2.07%, carbon production of 4.51%, LCoE of 0.73%, and NPC of 0.79% along with a decrease in NPV of 19.37%. To handle this critical scenery, only 1% additional diesel is required annually.

Table 5. Techno-economic performance considering critical case studies.

Parameters	Value
Operating costs ($/kWh)	0.197
Annual carbon emission (tons)	16.67
LCoE ($/kWh)	0.5690
NPV ($)	2.4085×10^4
NPC ($/year)	8.5067×10^4

4.4. Sensitivity Analysis

In this techno-economic analysis, a sensitivity analysis is conducted to determine the influences of fuel price, useful lifespan, and discount rate variations on the system's LCoE and NPV. Figure 14 shows the influence of the discount rate (d) on the LCoE and NPV of the proposed offshore DC MG networks. The value of LCoE increases with respect to the change in discount rate, whereas NPV decreases. It is clear from the figure that the discount rate has a significant influence on the LCoE and NPV of the system. The LCoE rises from 0.45 $/kWh to 0.78 $/kWh when the discount rate varies from 3% to 15%.

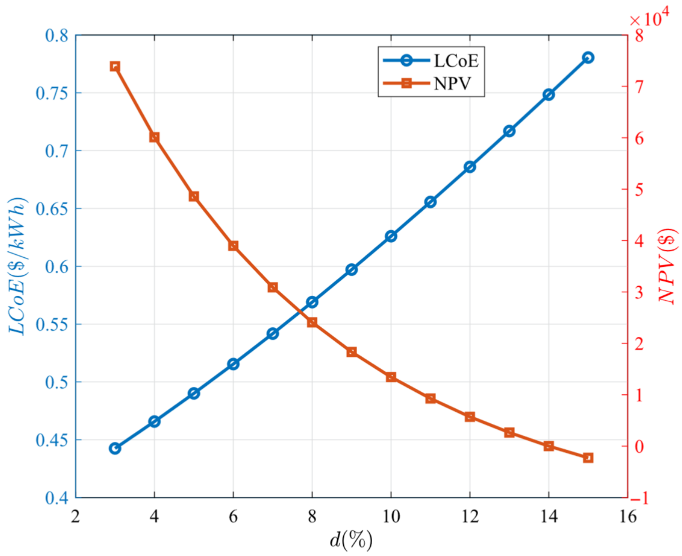

Figure 14. Impact of discount rate variations on the LCoE and NPV.

Figure 15 illustrates the impact of the useful lifespan (n) on the LCoE and NPV of the proposed DC MG networks on the offshore platforms. The LCoE exhibits a decrease in value corresponding to variations in the useful lifespan, while the NPV shows an increase. The figure demonstrates that the useful lifespan significantly affects the LCoE and NPV of the system. The LCoE decreases from 0.74 $/kWh to 0.52 $/kWh as the useful lifespan changes from 10 to 30 years.

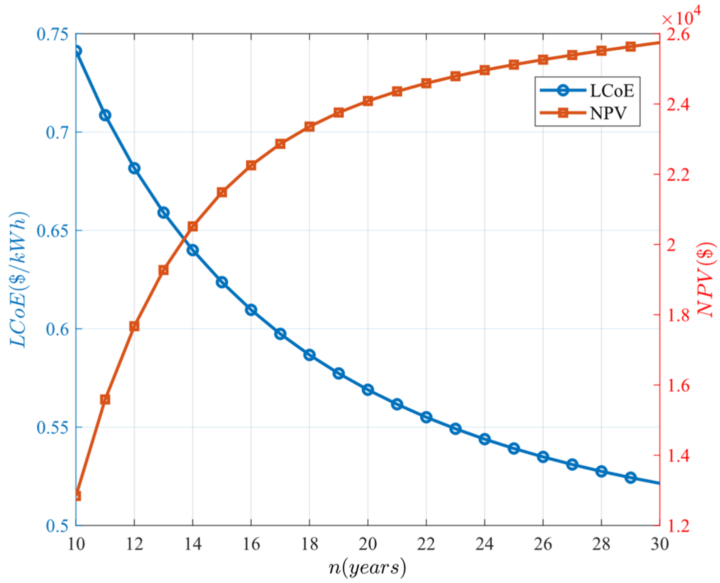

Figure 15. Impact of useful lifespan variations on the LCoE and NPV.

Figure 16 depicts the effect of the diesel price on the LCoE and NPV of the designed DC MG networks in offshore platforms. The LCoE rises with changes in the fuel price, although the NPV declines. The illustration indicates that the diesel price slightly influences the LCoE and NPV of the system. The LCoE increases from 0.567 $/kWh to 0.577 $/kWh when the fuel price variation extends from 3% to 15%.

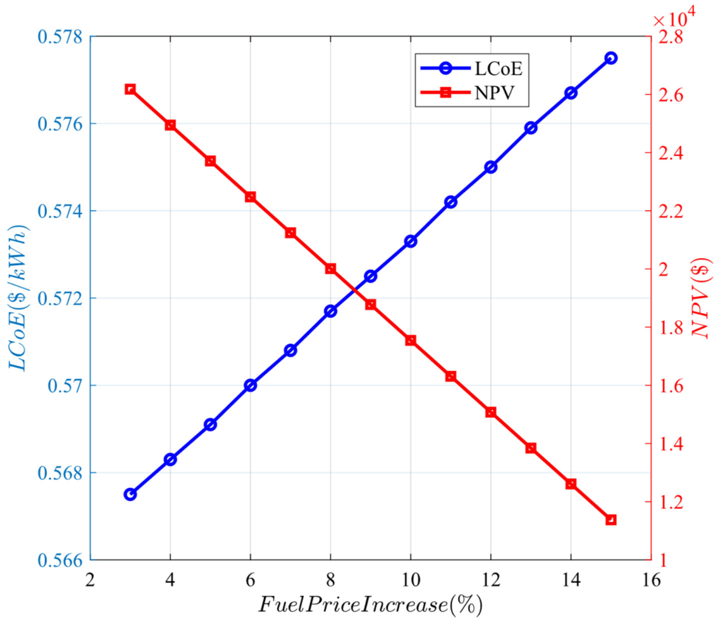

Figure 16. Impact of fuel price variations on the LCoE and NPV.

4.5. Discussion

The techno-economic analysis demonstrates that the proposed RES-based offshore DC MG significantly outperforms the conventional diesel-only system in terms of fuel consumption, operating cost, and emissions. These improvements are mainly because of the increased integration of RESs, which reduces dependence on diesel generation and associated fuel costs. The results are consistent with previous studies on hybrid MGs, which report similar benefits from RES integration [11–14]. However, unlike most existing works focusing on solar–wind systems, this study highlights the effectiveness of wave energy, which is particularly suitable for offshore environments due to its high availability and predictability. The scenario-based analysis confirms that the proposed DC MG system maintains reliable operation under both short-term and prolonged RES unavailability, demonstrating its robustness. In addition, the sensitivity analysis shows that the system is less affected by fuel price variations compared to diesel-based systems, reinforcing its economic advantage.

5. Conclusions

The techno-economic analysis shows that the proposed offshore DC MG with a sophisticated energy management system offers a cost-effective solution, reducing operating costs and carbon emissions. This analysis utilises actual generation and load profiles, indicating practical insights into the operational feasibility of RES-based DC MGs in offshore environments. The DC MG network incorporates a battery storage unit alongside a cost-effective energy management system to balance the generation and load demand. The energy management system guarantees cost-effective operation, minimising both operating costs and environmental impacts. The RES-based offshore DC MG system yields an operational expense of 0.193 $/kWh, annual carbon emissions of 15.95 tons, an LCoE of 0.5649 $/kWh, an NPC of 8.44×10^4 $/year, and an NPV of 2.987×10^4 $. The results indicate that the proposed system significantly reduces operating costs by 77.56%, diesel dependency by 93%, carbon production by 89.50%, and LCoE by 36.17% compared with diesel-based offshore DC MGs. Sensitivity analysis reveals that the discount rate and useful lifespan have a significant influence on the LCoE and NPV, whereas fuel price has a slight impact on the LCoE and NPV. These findings offer a decision-making framework for the design and implementation of RES-based DC MGs on offshore platforms. Future work will extend the proposed framework to multiple geographical locations in order to assess its performance under diverse climatic and wave conditions and to further enhance the generalisability of the results. Although the present study incorporates system lifespan in the sensitivity analysis to capture lifecycle effects from an economic viewpoint, a detailed assessment of technological risks, component degradation, maintenance requirements, and long-term reliability in harsh offshore environments is beyond the scope of this work. These aspects should be investigated in future studies to further strengthen the practical assessment of offshore DC MG deployment.

Author Contributions: Conceptualization, A.H., M.N., X.W., E.F., W.H. and P.A.H.; Methodology, A.H., M.N., X.W., E.F., W.H. and P.A.H.; Software, A.H., M.N., X.W., E.F., W.H. and P.A.H.; Validation, A.H., M.N., X.W., E.F., W.H. and P.A.H.; Formal analysis, A.H., M.N., X.W., E.F., W.H. and P.A.H.; Investigation, A.H., M.N., X.W., E.F., W.H. and P.A.H.; Resources, A.H., M.N., X.W., E.F., W.H. and P.A.H.; Data curation, A.H., M.N., X.W., E.F., W.H. and P.A.H.; Writing—original draft, A.H., M.N., X.W., E.F., W.H. and P.A.H.; Writing—review & editing, A.H., M.N., X.W., E.F., W.H. and P.A.H.; Visualization, A.H., M.N., X.W., E.F., W.H. and P.A.H.; Supervision, M.N., X.W., E.F., W.H. and P.A.H.; Project administration, M.N., X.W., E.F., W.H. and P.A.H.; Funding acquisition, M.N., X.W., E.F., W.H. and P.A.H. All authors have read and agreed to the published version of the manuscript.

Funding: The authors express gratitude for financial assistance from the Blue Economy Cooperative Research Centre, which was founded and is financed by the Australian Government's CRC Programme, grant number CRC-20180101. The CRC programme facilitates industry-driven cooperation among industry, researchers, and the community.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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