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Offshore Platform Decarbonization Methodology Based on Renewable Energies and Offshore Green Hydrogen: A Techno-Economic Assessment of PLOCAN Case Study

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Abstract: The decarbonization of offshore infrastructures is relevant to advancing global climate goals. This study presents a renewable-based energy system tailored for the Oceanic Platform of the Canary Islands (PLOCAN), designed to achieve full energy autonomy and eliminate greenhouse gas emissions. A hybrid configuration integrating photovoltaic panels, vertical-axis wind turbines, lithium-ion batteries, a proton exchange membrane (PEM) electrolyzer, and a PEM fuel cell was developed and evaluated through detailed resource assessment, system simulation, and techno-economic analysis under real offshore constraints. The results confirm that complete decarbonization is technically feasible, with a net present cost approximately 15% lower than the current diesel-based system and a total suppression of pollutant emissions. Although the transition entails a higher initial investment, the long-term economic and environmental gains are substantial. Offshore green hydrogen emerges as a key vector for achieving energy resilience and sustainability in isolated marine infrastructures, offering a replicable pathway towards fully decarbonized ocean platforms.

Keywords: offshore green hydrogen; renewable energy; offshore platform; decarbonization

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1. Introduction

The global energy transition is increasingly being shaped by the urgent need to decarbonize hard-to-abate sectors, among them offshore infrastructures, which remain heavily reliant on fossil fuels for power generation. Remote maritime platforms, particularly those operating in islanded or semi-autonomous modes, have historically depended on diesel generators. This model entails considerable operational costs, logistical challenges, and significant greenhouse gas (GHG) emissions [1].

Decarbonizing these systems is no longer optional but rather critical to achieving regional and international climate goals. The transition toward renewable-based autonomous microgrids has been facilitated by the integration of robust modelling tools, cost declines in solar and wind technologies, and recent breakthroughs in hydrogen (H_2) production and storage. Green hydrogen, in particular, has emerged as a key enabler of offshore energy autonomy, offering a viable path for long-term energy storage and dispatchability in the face of renewable intermittency [2]. There are technological challenges to be addressed regarding the storage and transportation of hydrogen from its offshore production sites. In the case of tank storage, and given hydrogen's low density, compression or even liquefaction becomes essential. However, these processes require significant energy input and do not fully resolve the issue of the large volume required for storage [3–6]. Transportation is another key factor, although the focus of this study is on the use of hydrogen at the same location where it is produced.

Recent comprehensive reviews highlight that offshore green hydrogen, despite its current cost disadvantages compared to onshore production, holds strong potential to decarbonize isolated sectors by leveraging abundant offshore wind and minimizing land use conflicts [7]. Moreover, advancements in offshore hybrid renewable energy systems integrating wind, solar, and hybrid energy storage technologies demonstrate increasing technical feasibility to overcome intermittency challenges [8]. Several pioneering projects already demonstrate the growing technical and strategic importance of integrating hydrogen into offshore energy systems. For example, the Seaworthy project—backed by the EU Innovation Fund—will soon be deployed at the PLOCAN offshore test site in the Canary Islands, aiming to validate a hybrid offshore platform combining floating wind, wave energy, and onboard hydrogen generation via electrolysis [9,10]. Similarly, PosHYdon, the first offshore hydrogen pilot in the Dutch North Sea, is converting an existing gas platform into a renewable hydrogen production unit, combining wind-powered electrolysis with existing gas infrastructure to evaluate operational feasibility under real offshore conditions [11]. Complementary studies, such as those conducted in the Faroe Islands, underscore the importance of combining offshore renewable generation with hydrogen production to enhance energy independence and meet decarbonization targets, demonstrating that offshore hydrogen can significantly reduce reliance on imported fossil fuels while requiring strategic policy support to achieve economic viability [12]. Moreover, advanced energy management strategies using model predictive control (MPC) have shown promise in optimizing hydrogen production offshore, dynamically balancing renewable energy variability and minimizing electrolyzer switching, thus enhancing the operational efficiency and lifetime of hydrogen generation assets [13].

However, despite these pioneering initiatives, there remains a significant gap in the literature regarding the comprehensive modelling and techno-economic assessment of fully renewable and hydrogen-integrated energy systems specifically tailored to small-scale offshore scientific platforms operating under highly variable occupancy and environmental conditions. Most existing studies focus either on large offshore wind farms or on pilot hydrogen production systems, but few address the unique operational constraints and spatial limitations faced by platforms like PLOCAN. This study seeks to fill that gap by proposing and evaluating a tailored, site-specific energy system for offshore research infrastructure.

Against this backdrop, the present study explores the viability of a fully renewable and hydrogen-integrated power system for the PLOCAN offshore platform. Located off the northeast coast of Gran Canaria, PLOCAN functions as a multipurpose scientific infrastructure, supporting marine technology validation and clean energy demonstration. The platform's operational profile, characterized by intermittent occupancy and load variability, presents a unique opportunity to pilot an innovative, low-carbon energy system that could inform broader offshore energy decarbonization efforts. The proposed solution integrates photovoltaic solar panels, vertical-axis wind turbines, a proton exchange membrane (PEM) electrolyzer, lithium-ion battery storage, and a PEM fuel cell. Hydrogen acts as both an energy carrier and a storage buffer, produced during periods of renewable surplus and converted back to electricity via fuel cells when generation is insufficient. System performance is evaluated through detailed modelling and simulation of PLOCAN's power profile under site-specific environmental conditions, accounting for spatial constraints, structural limitations, and seasonal variability in wind and solar resources.

The main objectives of this work are therefore threefold: (1) to design a hybrid renewable hydrogen energy system capable of achieving full energy autonomy for PLOCAN,

(2) to assess the technical feasibility and operational performance of the proposed system under realistic offshore conditions, and (3) to perform a techno-economic analysis comparing the proposed configuration to the current diesel-based model, thereby quantifying its potential economic and environmental benefits.

Beyond ensuring energy reliability, this hybrid renewable hydrogen architecture is assessed from a techno-economic standpoint. Metrics such as the net present cost (NPC), levelized cost of energy (LCOE), and renewable penetration rate are used to benchmark performance against the current diesel-based system.

This study contributes to the growing body of knowledge on offshore renewable integration and green hydrogen deployment. It provides a replicable framework for evaluating energy autonomy solutions in remote marine environments, with PLOCAN serving as a microcosm for potential applications across the broader offshore research, defense, and blue economy domains. The findings aim to inform both policy and engineering strategies that support the transition toward resilient and fully decarbonized offshore infrastructures.

The structure of this paper is organized as follows: Section 2 describes the methodology, including resource assessment, load profiling, and system design criteria. Section 3 presents the modelling framework and assumptions. Sections 4 and 5 discuss the simulation results and the techno-economic analysis. Finally, Section 6 summarizes the main conclusions and outlines directions for future research.

2. Materials and Methods

This section describes the tool employed, the approach followed and the procedures that form the basis of the proposed method to decarbonize an isolated microgrid within an offshore platform combining renewable energies and offshore green hydrogen production.

2.1. HOMER Pro Software for Planning and Optimizing Multiple Energy Resources

HOMER Pro software (version 3.18.4) is a widely used simulation tool in the industrial and energy sectors, as well as in scientific research [14–19], as it provides a comprehensive techno-economic analysis of proposed energy systems, along with optimization recommendations. HOMER Pro models hybrid systems, offering the ability to simulate a broad range of renewable alternatives. It allows for detailed hourly simulations to assess the energy balance between load and generation, making it particularly useful for isolated or weakly connected systems. Additionally, HOMER Pro enables economic analysis of the project, estimating capital expenditure (CAPEX), operational expenditure (OPEX), and levelized cost of energy (LCOE) using an optimization algorithm to determine the optimal solution. However, it does not evaluate electrical dynamics, such as parameter stability or transients [18,20]. Moreover, it does not analyze network energy flows and, consequently, cannot assess circuit and component overloads, but these aspects are more closely related to implementation than planning, which constitutes the main focus of our study. In Ref. [21], for instance, both aspects are addressed; however, the dynamic electric analysis is explored in less depth.

2.2. Detailed Description of the Procedure

The mains steps of the method are shown in Figure 1. This procedure intends to be applied to any offshore platform deployed in any remote location all over the world in order to decarbonize the normal operation of the energy system with the sole contribution of the renewable resources of its environment. For the assessment of the current scenario and alternatives, a lifetime must be defined according to the obsolescence of the microgrid as a whole, which will be the time-basis for the economic feasibility assessment.

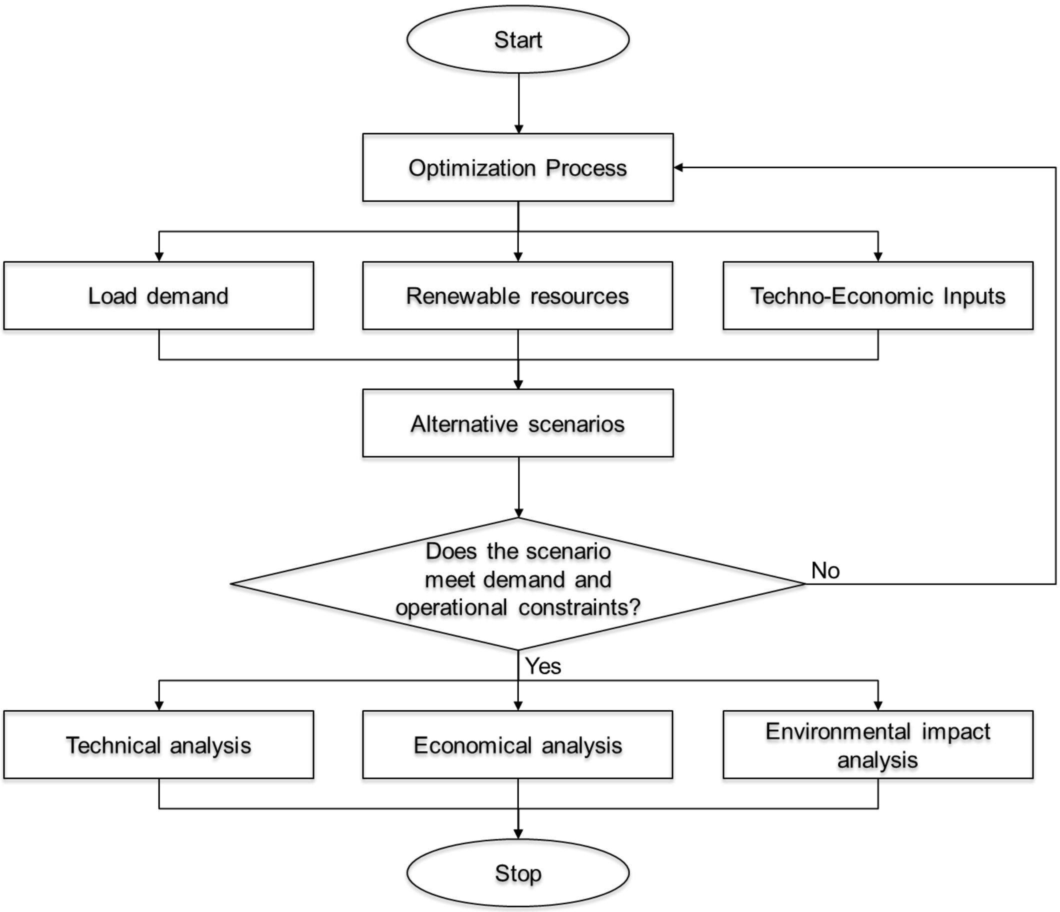

Figure 1. Flow chart of the proposed method's steps.

2.2.1. Renewable Resource and Demand Analysis

A comprehensive assessment of renewable energy potential is essential for defining feasible alternatives. This study uses data from MERRA-2 (https://gmao.gsfc.nasa.gov/reanalysis/merra-2/, accessed on 26 March 2025) (Modern-Era Retrospective analysis for Research and Applications, version 2), a global meteorological dataset that combines satellite observations, ground-based measurements, and climate models.

This global coverage ensures the model's applicability to other regions; consequently, the methodology is designed to be generalizable and replicable globally. For solar photovoltaic (PV) generation, time-series data of solar irradiance are analyzed. For wind energy, wind speed datasets are evaluated.

The platform's energy demand is recorded using a grid analyzer over a representative period that includes varying operational conditions (high, medium, and low demand). Since the system is completely isolated, the daily demand curve is constructed based on the maximum recorded hourly values to ensure conservative estimates and safety margins.

2.2.2. Reference System Modelling

The reference energy model represents an isolated microgrid entirely powered by fossil fuel-based generation. This model is based on a real, currently operational offshore installation, and is used to project the necessary modifications required to ensure the complete decarbonization. The interventions proposed can either adapt the energy management of an existing facility to a low-carbon framework or extend the infrastructure's operational life for new sustainable purposes, thereby generating added value and contributing to the energy transition [22,23].

The model simulates a one-year period with hourly resolution, assuming a continuous energy balance between generation and demand, achievable due to the high dispatchability of fossil-based systems. Therefore, the model reflects an optimized energy operation under the current system configuration.

The fossil fuel generation is modelled using the manufacturers' consumption curves, accounting for pollutant emissions associated with electricity production. This enables accurate estimation of fuel consumption and corresponding emissions for any given demand.

For the economic analysis, investment and operation and maintenance (O&M) costs are included, as well as the lifetime of the generators. Additionally, the model incorporates environmental penalties related to emissions of CO_2, CO, unburned hydrocarbons, particulate matter, and NOx, as established in Ref. [24].

2.2.3. Model Validation

The validation of the fossil generation model relies on comparing the modelled and actual annual fuel consumption. The only input required for fossil-based generation is the amount of fuel burned. The model uses the generator's power curve to estimate this value, and the comparison of both values establishes the base of the deviations of the model compared to reality with the aim of knowing the assumed error in the proposed alternatives.

2.2.4. Formulation and Modelling of New Alternative Scenarios

This stage focuses on identifying renewable alternatives to replace fossil fuel generation, while considering the constraints and limitations specified in subsequent steps. The evaluation of alternatives follows a techno-economic approach, requiring the definition of input parameters for the selected simulation tool. The main objective is to meet the offshore platform's energy demand, as defined and validated in the reference model. The adjustable variables represent potential renewable energy sources, selected based on site-specific feasibility studies. Once technically feasible options are established, economic variables are evaluated to determine the optimal solutions among them.

The process is structured as follows:

i. Resource assessment: According to the location of the offshore platform, renewable resources are evaluated using MERRA-2 data. These data provide insight into the local potential for renewable energy generation.
ii. Scenario definitions: Technically feasible scenarios are defined to ensure energy balance. HOMER Optimizer™ version 3.18.4 is employed to identify optimal system configurations capable of covering the demand. However, this optimization tool is only available for four devices and is not applicable to fuel cell modules, requiring manual pre-sizing in such cases and selecting the most appropriate elements to be optimized using this tool.
iii. Spatial and operational constraints: Based on the feasible solutions, constraints must be established, such as the available surface area and compatibility with platform operations. Renewable energy systems are generally space-intensive, and potential interference with ongoing offshore activities must be minimized. This step may lead to a reduction in or the elimination of some alternatives proposed in step ii.
iv. Electrical architecture preservation and storage requirements: The objective is to minimize intervention in the existing electrical infrastructure, especially in terms of cabling. Consequently, the maximum allowable power transfer remains unchanged, and energy storage systems become critical for ensuring supply reliability due to the intermittency of renewables. High-power energy storage solutions are also needed to enhance transient stability by providing synthetic inertia and supporting grid stability during prolonged disturbances [25,26]. The inherent architecture of offshore power

systems—comprising multiple generation and consumption units—further increases the need for stabilizing strategies and components [27].

v. Selection of the optimized alternatives. After applying constraints to technically viable solutions, the most promising options are selected based on economic and environmental performance.

2.2.5. Techno-Economic and Pollutant Emissions Analysis of the New Alternative Scenarios

The technical feasibility of each alternative is assessed based on its ability to ensure energy balance throughout the year while respecting the platform's operational constraints. Scenarios are tested under the assumption of isolated grid operation, emphasizing the role of renewable energy generation supported by lithium-ion batteries and, where applicable, hydrogen storage systems.

Renewable penetration is prioritized, and diesel generation is relegated to backup or emergency roles. The configuration of renewable sources is tailored to match available areas and structural constraints. The selected storage system provides the necessary energy management capacity to maintain supply stability and compensate for the intermittency of renewables. The economic performance of each alternative scenario compared with the reference system model is evaluated based on the net present cost (NPC), levelized cost of energy (LCOE), capital expenditure (CAPEX), and operational expenditure (OPEX).

The pollutant emissions associated with power generation are evaluated for the proposed alternatives and compared again with the reference system.

3. Case Study: The Oceanic Platform of the Canary Islands (PLOCAN)

The Oceanic Platform of the Canary Islands (PLOCAN) is a Unique Scientific and Technical Infrastructure (ICTS) designed to support and enhance marine research, technological development, and innovation. It plays a crucial role in advancing ocean sciences, renewable energy, and blue economy initiatives, while also fostering socio-economic activity in the Canary Islands region [23].

As a multi-purpose research facility, PLOCAN provides access to an extensive marine testing area, offering a real-sea environment for cutting-edge scientific experiments, prototype validation, and technological demonstrations. This capability is particularly relevant for sectors such as marine robotics, ocean observation, offshore renewable energy, and aquaculture.

PLOCAN features a Test Site that spans 23 km^2 of public-domain marine area, located off the northeast coast of Gran Canaria. This area reaches maximum depths of 600 m and serves as a strategic offshore laboratory, enabling researchers and industry stakeholders to conduct controlled experiments in an open-sea environment [28].

At the heart of this facility is located the PLOCAN offshore multipurpose platform, which is positioned 1.5 km off the northwest coast of Gran Canaria at a seabed depth of 30.5 m. Its proximity to deep waters, stable oceanographic conditions, and accessibility make it an ideal site for pioneering studies in wave and tidal energy, floating wind turbines, and autonomous marine systems.

3.1. The Infrastructure: The Offshore Platform of PLOCAN

The PLOCAN offshore multipurpose platform (see Figure 2) is built on a reinforced concrete caisson, which serves as the main support structure for additional operational elements. This caisson is anchored to the seabed, ensuring stability and resilience against oceanic forces, and provides a stable working environment for researchers, engineers, and operators involved in marine and offshore technology projects [28].

Figure 2. Offshore platform of PLOCAN (Gran Canaria).

The platform is equipped with an advanced intelligent power management system (SmartGrid), designed not only to optimize its own energy consumption but also to function as an isolated electrical testbed for marine energy prototypes deployed in its surroundings. This system efficiently integrates, regulates, and distributes the energy generated by these prototypes, ensuring optimal load balancing and stability. By providing a controlled real-sea environment for testing and validating emerging marine renewable energy technologies, the platform plays a crucial role in advancing offshore energy systems and facilitating their transition towards large-scale deployment.

The energy-related activities at PLOCAN align with national and European policies for sustainable energy development. According to Article 4 of Royal Decree 900/2015 [29], which regulates the administrative, technical, and economic conditions of electricity supply and self-consumption generation, the installation is classified as an isolated system. This means that the platform lacks any physical capacity for electrical connection to the national grid, either directly or indirectly, even through third-party infrastructure.

From a generation perspective, and in accordance with Law 24/2013 about the electrical sector [30], the PLOCAN offshore platform operates under a self-consumption model with no energy surplus injection into the main electrical grid. This classification allows for the testing of innovative energy generation technologies, such as floating photovoltaic systems, hydrogen production from seawater electrolysis, and hybrid renewable energy solutions.

3.2. H2Verde Project

The H2Verde Project [31], funded under the Complementary Plan for R&D in Renewable Energy and Hydrogen, seeks to transform the energy paradigm by reducing GHG emissions and promoting sustainable energy solutions. As part of this initiative, the PLOCAN platform will integrate a green H_2 production and storage system into its self-supply grid, enabling energy self-sufficiency while significantly minimizing reliance on fossil fuels. This transformation will establish the platform as a decarbonized, autonomous energy system, serving as a reference model for other offshore platforms, artificial islands, or simple isolated territories.

The proposed system will utilize renewable energy sources, including photovoltaic panels (PV system) and small-scale wind turbines (WTs) installed on the platform, as well as energy generated by deployed offshore prototypes. The electricity produced will be consumed directly by the platform, stored in an ion-lithium battery bank, and power a proton exchange membrane (PEM) electrolyzer, facilitating the conversion of water into H_2.

The generated H_2 will be stored and later converted back into electricity via a H_2 PEM fuel cell (PEMFC), ensuring, together with the batteries, a stable and reliable energy supply for the platform.

The lifetime of the new infrastructure has been established as 20 years due to the individual lifetime of the different equipment and the technological obsolescence, which is established as the time basis for the feasibility study of the current situation and the alternative scenarios. A discount rate of 8% and an inflation rate of 2% have been also considered.

3.3. Renewable Resources and Load

This subsection describes the available renewable energy resources on the PLOCAN test site as well as the load demand of the PLOCAN platform.

3.3.1. Available Renewable Resources

The offshore platform of PLOCAN is located at coordinates 28.01123° N, −15.384665° W, and benefits from favorable irradiance and wind conditions. Using MERRA-2 data via HOMER Pro's connection to NASA's Prediction of Worldwide Energy Resource (POWER) database, a representative meteorological year is simulated for the site.

Wind Resource

A one-year time series was created from the described meteorological predictive model, producing an hourly average wind speed dataset and referring to the altitude of the wind turbines' installation area above sea level. The value of 0.0002 m was selected as the surface roughness length, representative of a calm sea area. The monthly average wind speed in the deployment area is represented in Figure 3, and 7.26 m/s was obtained as the scaled annual average.

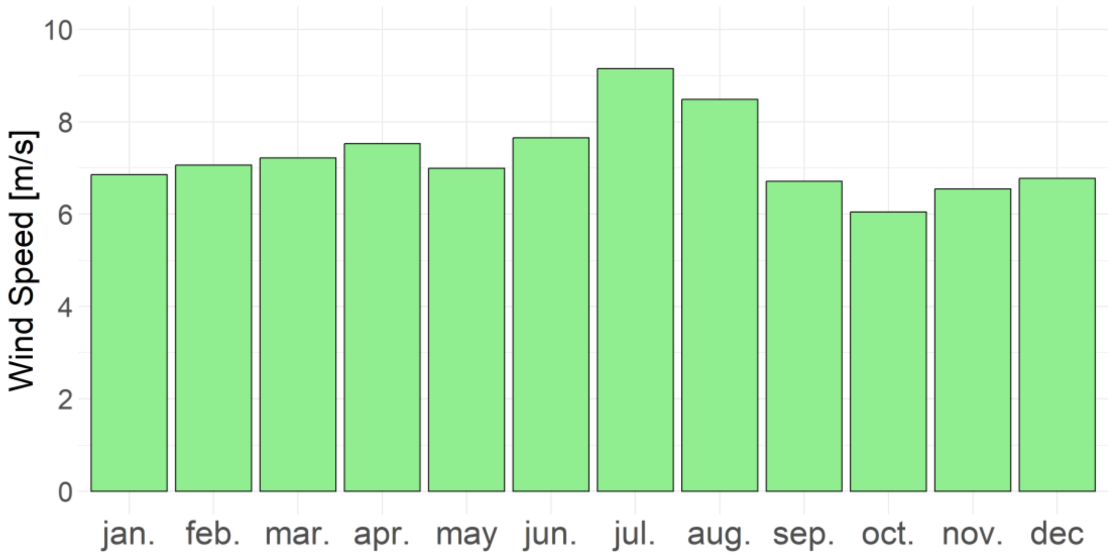

Figure 3. Monthly average wind speed at 28.01123° N, −15.384665° W.

Global Horizontal Irradiance Resource

Similar to the wind profile, an hourly average for global horizontal irradiance (GHI) dataset was created for the selected location, obtaining a time series summarized in Figure 4 and 5.40 kWh/m^2/day as the scaled annual average.

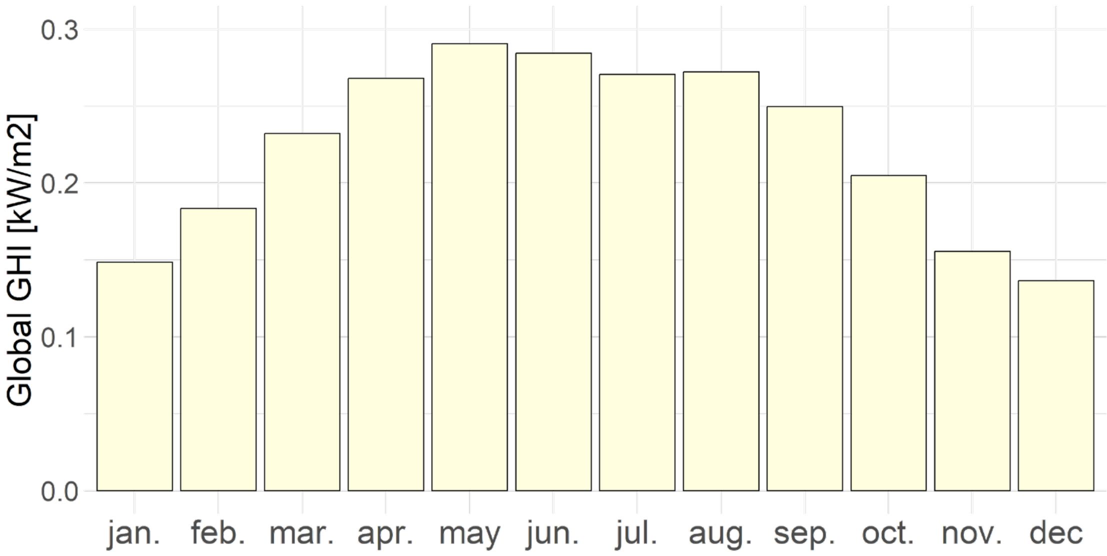

Figure 4. Monthly average for GHI at 28.01123° N, −15.384665° W.

3.3.2. PLOCAN Load Demand

The offshore platform of PLOCAN exhibits a peculiar load curve due to the fact that it remains unoccupied for a significant portion of the year. Access to the platform is restricted by metocean conditions—particularly significant wave height (<1.2 m)—resulting in access on approximately 80 days per year, with daily activities lasting 7–8 h.

A load demand reading was taken over a 14-day period of access to the offshore platform, where routine operation and maintenance tasks were carried out. The resulting load curves never exceeded the simplified scheme shown in Figure 5. Instead of using an average demand value and given that the system is fully off-grid, a conservative approach was established by considering the highest recorded demand in each hourly time slot as the hourly load for modelling the self-consumption grid, ensuring the system is robust to peak consumption.

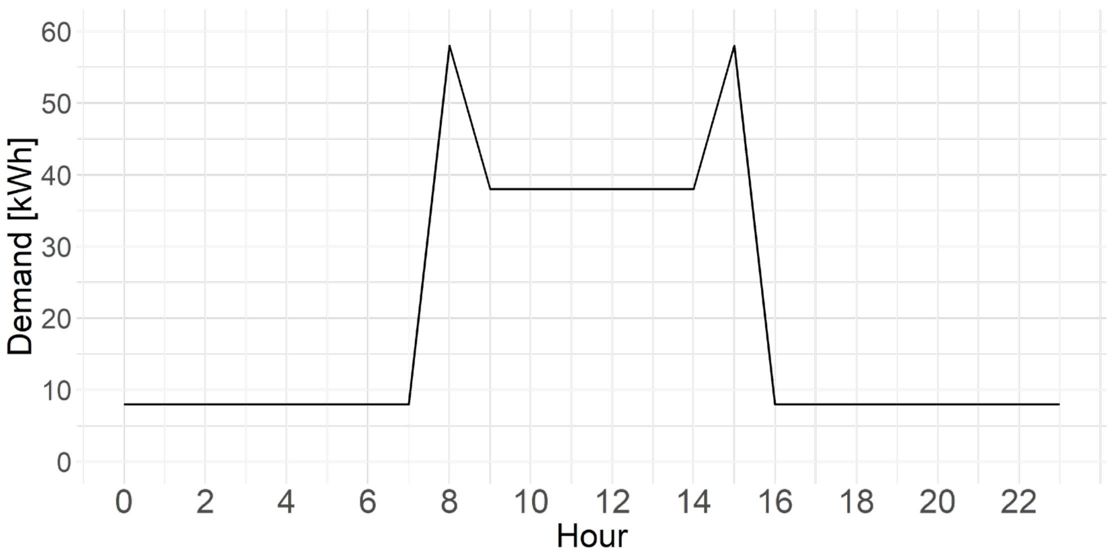

Figure 5. Daily curve demand.

Thus, there is no electricity demand when the platform is unoccupied. During the first and last hour of the access journey to the platform, the maximum recorded demand reached 58 kWh, while during intermediate hours, it never exceeded 30 kWh. These days of access are distributed throughout the year according to the probability that metocean conditions will permit access, using the historical series provided by the metocean buoy of Puertos del Estado Las Palmas Este (15.39° W, 28.05° N) [32].

3.4. Reference Model: Current PLOCAN SmartGrid

The current PLOCAN SmartGrid (See Figure 6) is an intelligent system designed to efficiently manage electricity generation and demand on its offshore platforms. It operates at a nominal voltage of 400 V (3-phase) with a nominal capacity of 1 MW and consists of the following key components:

i. A 0.4/20 kV transformer station, equipped with a 20 kV underwater cable, enabling the connection of an energy production prototype operating at medium voltage.
ii. Four generation feeders, each rated at 400 V/250 kW, dedicated to prototype connection. This generation capacity is not considered permanent, as the prototypes are under validation and operate only during specific testing campaigns lasting from weeks to several months.
iii. Four consumption feeders, each rated at 400 V/50 kW, supplying auxiliary services associated with the prototypes.
iv. A resistive load bank capable of consuming up to 1 MW of surplus energy, ensuring grid stability and energy balance.
v. A 400 V distribution panel, dedicated to the offshore platform's general load demand.
vi. Two diesel baseline generators, each rated at 508 kW, act as the synchronous reference for the isolated PLOCAN SmartGrid, ensuring stability and reliability within the energy system.

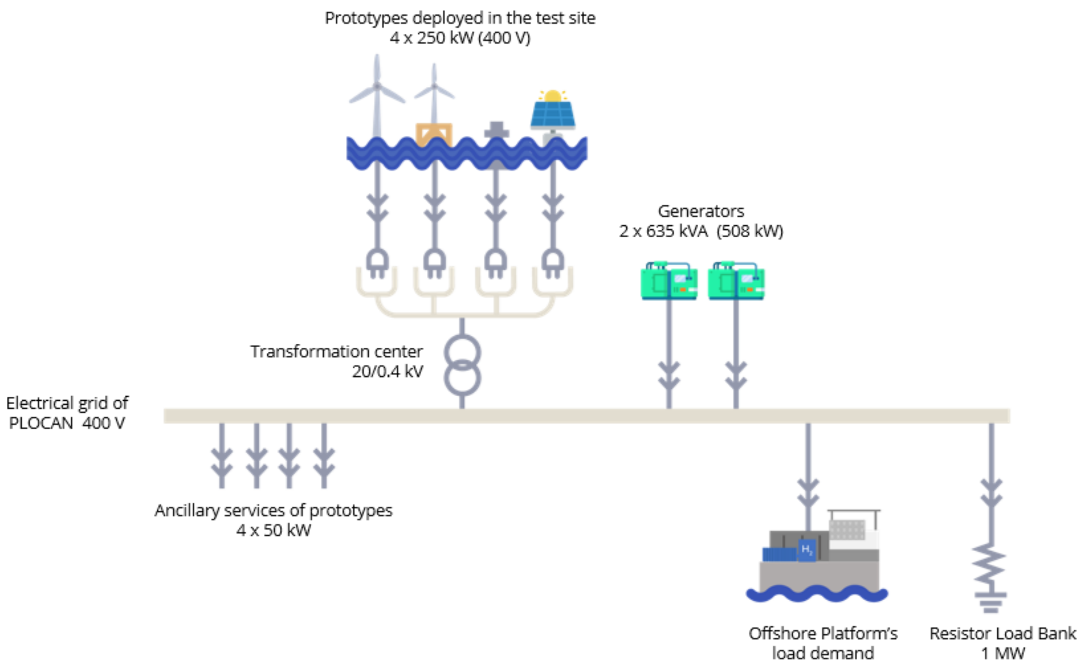

Figure 6. Electric diagram of the modelled system according to the current PLOCAN SmartGrid.

All technical and economic inputs for modelling the current system are summarized in Table 1.

Table 1. Inputs for the current PLOCAN SmartGrid model.

Diesel Genset 1 & 2 (CAT-635 kVA-508 kW)	
Reference generator capacity (kW)	508
Consumption at nominal capacity (L/h)	130.54
Intercept coefficient (L/h/kW)	0.0138
Slope (L/h/kW output)	0.2402
Initial capital and replacement (EUR)	183,000.00 [1]
O&M (EUR/op.hour)	5.00 [1]
Fuel price (EUR/L)	2.2 [2]
Emissions (g/L of fuel) [CO, unburned hydrocarbons, particulate matter, NOx]	2.09, 0.03, 0.06, 17.70 [3]
Minimum load ratio (%)	0 [1]
Lifetime (h)	90,000.00 [3]

[1] Real project data. [2] Actual cost based on the average invoiced over the past year, including marine bunkering. [3] HOMER Pro database.

3.5. Validation of the Reference Model

In order to validate the model, the simulated energy demand must match the measured annual demand of the platform. Since fossil-based generation is the sole permanent energy source in the current PLOCAN SmartGrid, energy demand is equal to the energy produced by the diesel generators.

For the year 2023, the platform's energy meters recorded 94,845 kWh of accumulated energy production and approximately 82,000 L of fuel consumption. HOMER Pro simulations using the actual generator model resulted in 98,920 kWh of electricity generation and 85,308 L of fuel use. The resulting deviations—4.30% in energy and 4.03% in fuel—are considered acceptable, thereby validating the model's reliability for simulating alternative future scenarios.

The economic data of this current scenario for a 20-year project lifetime are shown in Table 2.

Table 2. Economic assessment of the current PLOCAN SmartGrid model.

Genset 1 508 kW (kW)	Genset 2 508 kW (kW)	NPC (EUR)	LCOE (EUR/kWh)	OPEX (EUR/y)	CAPEX (EUR)
508	508	3.70 M	3.23	287,710	366,000

3.6. Constrains and Alternative Scenarios: Target PLOCAN SmartGrid

To achieve the decarbonization of the PLOCAN offshore platform, small-scale renewable generation systems are proposed, aligned with the spatial constraints and structural limitations of the facility. The area presents favorable wind and solar irradiation conditions, supporting the installation of rooftop and wall-mounted photovoltaic (PV) panels and small vertical-axis wind turbines. However, the rooftop is partially occupied by a helipad, which presents two key limitations: The PV system cannot be installed directly on the helipad surface, and the remaining rooftop area is affected by shading from the helipad structure. These types of restrictions are typical of offshore installations. The two existing diesel generators are retained as backup or emergency generation systems.

Due to the limited usable rooftop space, PV panels are also considered for installation on the southwest wall of the platform's building. Although the 90° panel slope is suboptimal for solar capture, the wall offers a usable surface area that does not interfere with platform operations. Following the approach in Ref. [23], the goal is to maximize the use of all available space.

Regarding wind energy, the prevailing wind direction is from the north (see Section 2.2.1), so wind turbines must be aligned perpendicularly to this direction. Given the structural limitations of the rooftop, turbines should be installed along the perimeter, where load-bearing capacity is sufficient. After spatial analysis, installation is limited to four vertical-axis turbines.

To ensure efficient energy management and guarantee system stability, next-generation lithium-ion battery systems are proposed for energy storage. These systems must offer both sufficient power output and storage capacity to support the microgrid under varying load and generation conditions.

Additionally, the platform serves as a testing site for marine energy prototypes, which are connected to 250 kW points on the SmartGrid. Therefore, it is desirable to have enough storage capacity to supply auxiliary services to these prototypes for extended periods using battery-stored energy. The storage and associated inverter will also smooth transients caused by prototype connection or disconnection [25,26].

Finally, green hydrogen is considered a key decarbonization vector. It enables the utilization of renewable energy surpluses to produce valuable products [19] and provides long-term storage capabilities that complement lithium-ion batteries, which suffer from self-discharge over time [33,34]. In this isolated microgrid, H_2 can be produced using renewable surpluses and later converted back to electricity (power-to-grid), avoiding curtailment and ensuring system flexibility.

On the other hand, the baseline generation from the PV system and wind turbines should cover the baseline consumption of the offshore platform to ensure complete decarbonization, so any additional energy input would be a surplus that would be dissipated in the resistance banks. However, an electrolyzer connected to the SmartGrid would consume, in addition to the occasional surplus from baseline generation, the energy generated during the trials by the prototypes deployed on the PLOCAN test bench and connected to the platform's SmartGrid.

The hydrogen production system will be integrated with the platform's existing desalination plant. The freshwater demand for electrolysis is already accounted for in the load assessment described in Section 3.3.2. Given the small scale of the planned electrolyzer and existing water storage capacity, no additional freshwater demand will be imposed on the system, which is an important consideration for scaling to larger offshore platforms [23].

Sequence of Operation of the Target PLOCAN SmartGrid

The operation of the proposed energy system is ruled by a defined sequence of energy flows, aiming to prioritize renewable sources while maintaining system reliability. The flow diagram representing the operational strategy is shown in Figure 7.

The load supply and generation sequences are described hereunder:

i. Load demand sequence
   Ancillary services of prototypes, if any, and load demand directly related to the offshore platforms are considered as a unique load demand. The battery systems function as a load when there is a renewable energy generation surplus, and the battery systems are not completely charged. If they are completely charged and there is a renewable energy generation surplus, the electrolyzer operates, generating and storing hydrogen. The hydrogen must always be produced using renewable energy. If this is not possible and any equipment requires a hydrogen demand, the model will indicate that the demand cannot be met.
ii. Power generation sequence
   Renewable generation is prioritized so fossil generation becomes backup generation. Renewable generation aims to supply the demand. Any surplus generation will charge the battery system. If there is no renewable generation and the battery system's charge drops below 20%, the available green hydrogen is used in the fuel cell to

rapidly charge the battery system in order to supply the demand. If it is not possible to meet the electricity demand, the backup diesel generators must operate.

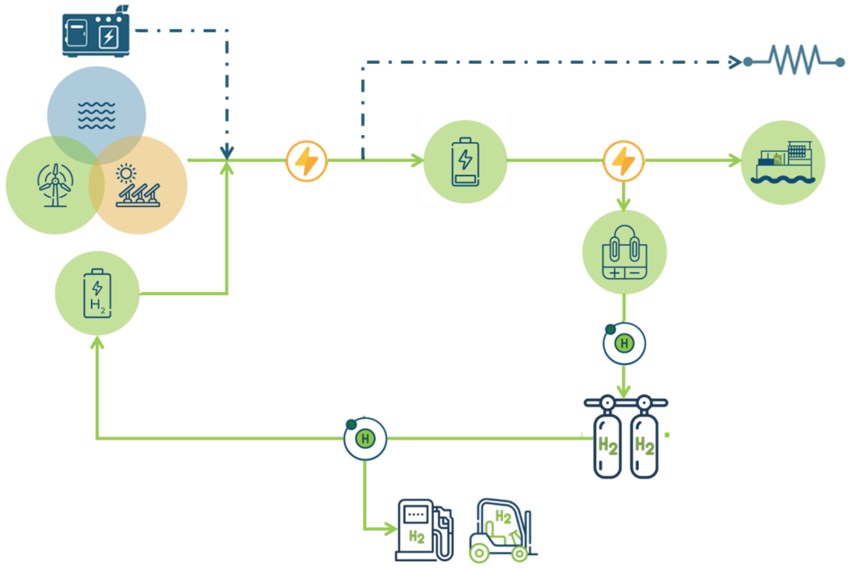

Figure 7. Scheme of the modelled system according to the target PLOCAN SmartGrid.

The flow chart is shown in Figure 8.

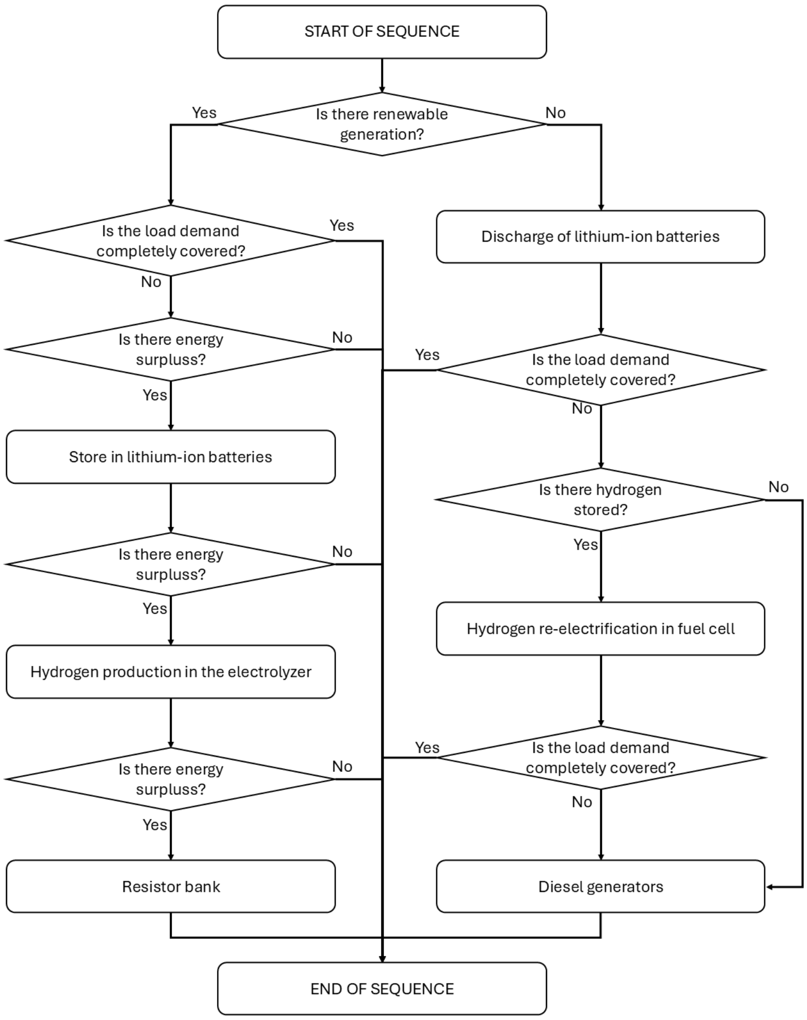

Figure 8. Sequence of operation of the target simulated system.

4. Results

In accordance with the provisions set out in Section 2.2.4, we initially proposed solutions to decarbonize the offshore platform in our case study, using pre-established renewable generators and energy storage elements. We then applied the relevant constraints, taking into account compatibility with the activities performed on the platform, and selected the most promising solutions based on a techno-economic assessment, while maintaining the primary objective of decarbonizing the platform energy system.

4.1. Approach to New Scenarios

To meet the demand described in Section 3.3, a variety of renewable generation and energy components are proposed, including:

i. Diesel Genset 1 and 2 (CAT-635 kVA-508 kW);
ii. PV system on the rooftop TRINA TSM-DEG19RC.20W 565 W (https://www.trinasolar.com/en-glb, accessed on 2 March 2025);
iii. PV system on the wall: CS7N-665MS-1500 V (https://www.csisolar.com/topbihiku7/, accessed on 6 February 2025);
iv. Vertical-axis wind turbines (tulip 5 kW, 12 m/s) (https://www.flowerturbines.com/, accessed on 14 March 2025);
v. PEM electrolyzer;
vi. PEMFC;
vii. Lithium-ion batteries Powercube M1C (https://en.pylontech.com.cn/, accessed on 2 February 2025));
viii. H_2 tank;
ix. Forklift powered by PEMFC as a H_2 load.

The input parameters for these components were introduced into the HOMER Pro model, as shown in Table 3. The simulation considered different configurations through several iterations, where techno-economic performance and spatial constraints were analyzed progressively.

Table 3. Inputs for the target PLOCAN SmartGrid model.

Diesel Genset 1 & 2 (CAT-635 kVA-508 kW)	
Initial capital and replacement (EUR)	183,000.00 [1]
O&M (EUR/op.hour)	5.00 [1]
Fuel price (EUR/L)	2.2 [2]
Emissions (g/L of fuel) [CO, unburned hydrocarbons, particulate matter, Nox]	2.09, 0.03, 0.06, 17.70 [3]
Fuel curve (kW, L/h)	[508, 130.54] [381, 96.84] [254, 66.97] [127, 38.81] [2]
Minimum load ratio (%)	0 [1]
Lifetime (h)	90,000.00 [3]
PV Panels on the Rooftop TRINA TSM-DEG19RC.20W 565 W (https://www.trinasolar.com/en-glb, accessed on 2 March 2025)	
Capacity (W)	565 [1]
CAPEX (EUR/565 W)	1480.77 [1]
OPEX (EUR/y)	260.16 [35]
Lifetime (y)	20
Derating factor (%)	90 [36]
Panel Slope (°)	28.05° [1]
Panel azimuth (°)	0.00°

Table 3. *Cont.*

PV Panels on the Wall: CS7N-665MS-1500 V (https://www.csisolar.com/topbihiku7/), accessed on 6 February 2025)	
Capacity (kW)	665 [1]
CAPEX (EUR/665 W)	3475.75 [1]
OPEX (EUR/y)	779.62 [35]
Lifetime (y)	20
Derating factor (%)	90 [36]
Panel slope (°)	90.00° [1]
Panel azimuth (°)	20.00°
Vertical-Axis Wind Turbines (tulip 5 kW, 12 m/s) (https://www.flowerturbines.com/), accessed on 14 March 2025)	
Capacity (kW)	5 [1]
CAPEX (EUR)	89,612.32 [1]
OPEX (EUR/y)	3584.49 [37]
Time (y)	20
Hub height (m)	40
Power curve	[38]
Overall loss factor (%)	20 [1]
PEM Electrolyzer	
CAPEX (EUR/kW)	100,161.42 [1]
OPEX (EUR/y)	50,080.71 [39]
Lifetime (y)	20 [1]
Efficiency (%)	78.80 [1]
Minimum load ratio (%)	5 [1]
PEMFC	
CAPEX (EUR/kW)	1829.88 [1]
OPEX (EUR/op.hour)	0.02 [40]
Minimum load ratio (%)	6 [1]
H_2 mass flow (rated power) (g/s)	1.15 [1]
Lifetime (h)	50,000 [39]
Lithium-Ion Batteries	
Total capacity (kWh)	872 [1]
String size (nr)	23 [1]
Nr of strings	8 [1]
Initial state of charge (%)	0 [1]
Minimum state of charge (%)	20 [1]
CAPEX (EUR)	560,000 [1]
OPEX (EUR/y)	1050 [40]
Lifetime (cycles)	6000 [1]
Lifetime (y)	15 [4]
H_2 Tank	
CAPEX (EUR/kg)	419.44 [1]
OPEX (EUR/y)	1449.60 [41]
Lifetime (y)	20 [1]
Forklift Powered by PEMFC	
Peak hydrogen load (kg/h)	0.25
Peak hydrogen load (kg/day)	0.25
Average hydrogen load (kg/day)	0.07
Charging hour per accessible day (h)	2

[1] Real project data. [2] Actual cost based on the average invoiced over the past year, including marine bunkering. [3] HOMER Pro database. [4] On a basis of 365 cycles/year.

4.1.1. First Iteration: Target PLOCAN SmartGrid with HOMER Optimizer™ Tool

Driven by the configuration of the SmartGrid as an isolated microgrid, energy storage high capacity (lithium-ion batteries) and the size of the associated inverter are key to ensuring grid stability [25,26], storage capacity is set to a value as close as possible to the SmartGrid maximum power of 1 MW, and the associated inverter is selected according to the maximum simultaneous power expected in the isolated microgrid. Based on these criteria, we selected 1 MWh storage capacity and an inversion rated at 500 kW. However, due to space restrictions, storage capacity needed to be reduced to 872 kWh with a 500 kW inverter. Both values were established as fixed variables in the model.

Likewise, the open space available on the platform limits the hydrogen storage beyond 172 kg at 200 bar, which corresponds to approximately 9600 L.

Due to software limitations, the HOMER Optimizer™ cannot be used on fuel cells, so we predefined the PEMFC power at 55 kW, closely matching the platform's peak hourly demand (58 kWh).

The four components optimized using the HOMER Optimizer™ tool are:

i. PV panels on the rooftop TRINA TSM-DEG19RC.20W 565 W;
ii. PV panels on the wall: CS7N-665MS-1500 V;
iii. Vertical-axis wind turbines (5 kW, 12 m/s);
iv. PEM electrolyzer.

According to the equipment described in Section 4.1, multiple scenarios were simulated, with several configurations achieving 100% renewable energy penetrations, as can be observed in Tables 4–6, where scenarios are ranked according to the economic feasibility (NPC and LCOE).

Table 4. Fixed variables in the target PLOCAN SmartGrid model in the first iteration.

55 kW PEMFC (kW)	Lithium-Ion Batteries (kW)	H_2 Tank (kg)
55	872	172.8

Table 5. First optimization using the HOMER Optimizer™ tool. Economic assessment of the alternatives in the target PLOCAN SmartGrid model.

PV Rooftop 565 W (kW)	PV Wall 665 W (kW)	Wind Turbines (nr)	Electrolyzer (kW)	Genset 1 508 kW (kW)	Genset 2 508 kW (kW)	NPC (EUR)	LCOE (EUR/kWh)	OPEX (EUR/y)	CAPEX (EUR)	Renewable Penetration (%)
32	83	-	4	-	-	1.59 M	1.38	21,485.80	1.34 M	100
23	80	1	4	-	-	1.64 M	1.43	21,930.83	1.38 M	100
38	79	-	3	508	-	1.70 M	1.49	17,557.71	1.50 M	100
38	79	-	3	-	508	1.70 M	1.49	17,557.71	1.50 M	100
29	74	1	3	508		1.74 M	1.52	17,449.37	1.54 M	100
29	74	1	3		508	1.74 M	1.52	17,449.37	1.54 M	100
38	79	-	3	508	508	1.83 M	1.60	12,620.45	1.68 M	100
29	74	1	3	508	508	1.86 M	1.63	12,512.10	1.72 M	100
40	-	1	13	508	-	1.90 M	1.66	57,427.66	1.24 M	52
40	-	1	13	-	508	1.90 M	1.66	57,427.66	1.24 M	52
41	-	-	13	508		1.91 M	1.67	65,677.46	1.15 M	40
41	-	-	13	-	508	1.91 M	1.67	65,677.46	1.15 M	40
-	138	-	3	508		1.95 M	1.70	18,006.95	1.74 M	99
-	138	-	3	-	508	1.95 M	1.70	18,006.95	1.74 M	99
-	92	3	3	508		1.97 M	1.72	19,355.95	1.74 M	100
-	92	3	3	-	508	1.97 M	1.72	19,355.95	1.74 M	100
28	-	9	3	-	-	1.97 M	1.72	27,983.74	1.65 M	100

Table 5. *Cont.*

PV Rooftop 565 W (kW)	PV Wall 665 W (kW)	Wind Turbines (nr)	Electrolyzer (kW)	Genset 1 508 kW (kW)	Genset 2 508 kW (kW)	NPC (EUR)	LCOE (EUR/kWh)	OPEX (EUR/y)	CAPEX (EUR)	Renewable Penetration (%)
40	-	1	13	508	508	2.03 M	1.77	52,490.39	1.42 M	52
41	-	-	13	-	-	2.04 M	1.78	60,740.20	1.33 M	40
-	92	5	5	-	-	2.05 M	1.79	25,512.33	1.76 M	100
-	138	-	3	508	508	2.07 M	1.81	13,069.68	1.92 M	99
-	92	3	3	508	508	2.09 M	1.83	14,418.68	1.93 M	100
-	183	-	6	508	508	2.12 M	1.85	23,053.50	1.85 M	100
-	-	14	4	-	-	2.41 M	2.10	32,693.88	2.03 M	100
-	-	14	4	508	-	2.54 M	2.22	27,856.11	2.22 M	100
-	-	14	4	-	508	2.54 M	2.22	27,856.11	2.22 M	100
-	-	14	4	508	508	2.66 M	2.33	22,918.84	2.40 M	100

Table 6. First optimization using the HOMER Optimizer^{TM} tool. Energy performance assessment of the alternatives in the target PLOCAN SmartGrid model.

55 kW PEMFC (kWh)	Genset 1 Energy Production (kWh/y)	Genset 2 Energy Production (kWh/y)	PV Rooftop 565 W Energy Production (kWh/y)	PV Wall 665 W Energy Production (kWh/y)	Wind Turbine Energy Production (kWh/y)	Lithium-Ion Battery Throughput (kWh/y)	Renewable Penetration (%)
1200	-	-	44,038	88,887	-	48,455	100
961	-	-	38,024	86,038	11,493	43,850	100
709	473	-	46,956	85,241	-	48,196	100
709	-	473	46,956	85,241	-	48,196	100
754	209	-	42,649	79,802	11,493	43,562	100
754	-	209	42,649	79,802	11,493	43,562	100
709	473	-	46,956	85,241	-	48,196	100
754	209	-	42,649	79,802	11,493	43,562	100
1078	47,179	-	47,752	-	11,493	59,098	52
1078	-	47,179	47,752	-	11,493	59,098	52
1270	59,074	-	48,101	-	-	66,105	40
1270	-	59,074	48,101	-	-	66,105	40
670	558	-	-	130,726	-	49,687	99
670	-	558	-	130,726	-	49,687	99
897	385	-	-	96,974	34,478	37,742	100
897	-	385	-	96,975	34,478	37,742	100
1974	-	-	41,740	-	103,432	32,014	100
1078	47,179	-	47,752	-	11,493	59,098	52
1270	59,074	-	48,101	-	-	66,105	40
341	-	-	-	96,975	57,463	32,736	100
670	558	-	-	130,726	-	49,687	99
897	385	-	-	96,975	34,478	37,742	100
201	-	-	-	153,687	-	47,609	100
2972	-	-	-	-	160,895	38,132	100
2962	2	-	-	-	160,895	38,132	100
2962	-	1.95	-	-	160,895	38,132	100
2962	2	-	-	-	160,895	38,132	100

4.1.2. Second Iteration: Target PLOCAN SmartGrid with Constraints Related to the PV System and Wind Turbines

Subsequent analysis revealed that some of the previously optimized PV system sizes exceeded the available rooftop and wall areas. A spatial feasibility analysis determined that the rooftop could support a maximum of 14.69 kW (26 modules) and the wall of the building a maximum of 62.51 kW (94 modules) due to shading and space considerations.

Additionally, the installation of wind turbines was limited to four units, located on the rooftop perimeter with sufficient structural support.

In this second iteration, the same simulation approach was used, but the above physical constraints were applied. The resulting configurations still included several 100% renewable energy solutions, although with higher NPC and LCOE values than those in the unconstrained scenario (See Tables 7–9).

Table 7. Fixed variables in the target PLOCAN SmartGrid model in the second iteration.

55 kW PEMFC (kW)	Lithium-Ion Batteries (kW)	H_2 Tank (kg)	PV Rooftop 565 W (kW)	PV Wall 665 W (kW)	Wind Turbines (nr)
55	872	172.8	<14.69	<62.51	<4

Table 8. Second optimization with first constraints. Economic assessment of the alternatives in the target PLOCAN SmartGrid model.

PV Rooftop 565 W (kW)	PV Wall 665 W (kW)	Wind Turbines (nr)	Electrolyzer (kW)	Genset 1 508 kW (kW)	Genset 2 508 kW (kW)	NPC (EUR)	LCOE (EUR/kWh)	OPEX (EUR/y)	CAPEX (EUR)	Renewable Penetration (%)
14.69	62.51	3	5	-	-	1.69 M	1.48	23,796.14	1.41 M	100
14.61	56.98	-	13	508	-	1.80 M	1.57	36,694.36	1.38 M	78
14.61	56.98	-	13	-	508	1.80 M	1.57	36,694.36	1.38 M	78
14.69	62.51	3	4	508	-	1.81 M	1.58	19,587.08	1.59 M	100
14.69	62.51	3	4	-	508	1.81 M	1.58	19,587.08	1.59 M	100
14.61	56.98	-	13	508	508	1.93 M	1.68	31,757.10	1.56 M	78
14.69	62.51	3	4	508	508	1.94 M	1.69	14,649.82	1.77 M	100
-	62.51	1	13	508		1.97 M	1.72	44,237.08	1.46 M	69
-	62.51	1	13	-	508	1.97 M	1.72	44,237.08	1.46 M	69
-	62.51	-	13	508		1.97 M	1.72	52,032.60	1.37 M	58
-	62.51	-	13	-	508	1.97 M	1.72	52,032.60	1.37 M	58
14.69	-	1	13	508		2.01 M	1.75	72,402.59	1.17 M	30
14.69	-	1	13	-	508	2.01 M	1.75	72,402.59	1.17 M	30
10.48	-	-	13	508	-	2.08 M	1.82	87,211.73	1.07 M	9
10.48	-	-	13	-	508	2.08 M	1.82	87,211.73	1.07 M	9
-	62.51	1	13	508	508	2.10 M	1.83	39,299.81	1.64 M	69
-	62.51	-	13	508	508	2.10 M	1.83	47,095.33	1.55 M	58
14.69	-	1	13	508	508	2.13 M	1.86	67,465.32	1.35 M	30
10.48	-	-	13	508	508	2.20 M	1.92	82,274.46	1.25 M	9
-	-	4	13	508		2.21 M	1.93	70,233.48	1.40 M	38
-	-	4	13		508	2.21 M	1.93	70,233.48	1.40 M	38
-	-	4	13	508	508	2.34 M	2.04	65,296.22	1.58 M	38

Table 9. Second optimization with first constraints. Energy performance assessment of the alternatives in the target PLOCAN SmartGrid model.

55 kW PEMFC (kWh)	Genset 1 Energy Production (kWh/y)	Genset 2 Energy Production (kWh/y)	PV Rooftop 565 W Energy Production (kWh/y)	PV Wall 665 W Energy Production (kWh/y)	Wind Turbine Energy Production (kWh/y)	Lithium-Ion Battery Through-put (kWh/y)	Renewable Penetration (%)
1654	-	-	26,779	67,502	34,478	37,008	100
590	21,821	-	26,640	61,528	-	57,191	78
590	-	21,821	26,640	61,528	-	57,191	78
1198	387	-	26,779	67,502	34,478	37,061	100
1198	-	387	26,779	67,502	34,478	37,061	100
590	21,821	-	26,640	61,528	-	57,191	78
1198	387	-	26,779	67,502	34,478	37,061	100

Table 9. *Cont.*

55 kW PEMFC (kWh)	Genset 1 Energy Production (kWh/y)	Genset 2 Energy Production (kWh/y)	PV Rooftop 565 W Energy Production (kWh/y)	PV Wall 665 W Energy Production (kWh/y)	Wind Turbine Energy Production (kWh/y)	Lithium-Ion Battery Through-put (kWh/y)	Renewable Penetration (%)
1039	30,268	-	-	67,502	11,493	55,254	69
1039	-	30,268		67,502	11,493	55,254	69
892	41,530	-	-	67,502	-	62,322	58
892	-	41,530	-	67,502	-	62,322	58
1394	68,752	-	26,779	-	11,493	66,879	30
1394	-	68,752	26,779	-	11,493	66,879	30
971	90,050	-	19,111	-	-	80,898	9
971	-	90,050	19,111	-	-	80,898	9
1039	30,268	-	-	67,502	11,493	55,254	69
892	41,530	-	-	67,502	-	62,322	58
1394	68,752	-	26,779	-	11,493	66,879	30
971	90,050	-	19,111	-	-	80,898	9
1038	61,366	-		-	45,970	63,638	38
1038	-	61,366	-	-	45,970	63,638	38
1038	61,366	-	-		45,970	63,638	38

4.1.3. Third Iteration: Target PLOCAN SmartGrid with Higher Green H_2 Production Capacity

Although the second iteration met the platform's energy needs, an additional constraint was introduced: the system should be capable of absorbing surplus energy from prototype trials connected to the 250 kW feeders on the testbed.

In the event that prototypes are connected to the SmartGrid, all the generated energy will be used to meet the auxiliary services of the prototypes themselves, and the rest will be derived to the resistance banks for dissipation. In order to avoid this, it is proposed to increase the green H_2 production capacity, considering the available area, and ensuring that this capacity is near to industrial scale.

In Ref. [42], the optimal combination of energy storage technologies to support fully renewable systems is proposed. According to the case studies considered in this analysis, the H_2 production system is sized to cover 30% of the renewable generation capacity. Based on this, a 100 kW electrolyzer is proposed to cover 320 kW—with the prototypes connected to the 250 kW feeders—which is the historical maximum power capacity connected to the SmartGrid simultaneously (See Tables 10–12).

Table 10. Fixed variables in the target PLOCAN SmartGrid model in the third iteration.

55 kW PEMFC (kW)	Lithium-Ion Batteries (kW)	H_2 Tank (kg)	PV Rooftop 565 W (kW)	PV Wall 665 W (kW)	Wind Turbines (nr)	Electrolyzer (kW)
55	872	172.8	<14.69	<62.51	<4	100

Table 11. Third optimization with the 100 kW electrolyzer. Economic assessment of the alternatives in the target PLOCAN SmartGrid model.

PV Rooftop 565 W (kW)	PV Wall 665 W (kW)	Wind Turbines (nr)	Genset 1 508 kW (kW)	Genset 2 508 kW (kW)	NPC (EUR)	LCOE (EUR/kWh)	OPEX (EUR/y)	CAPEX (EUR)	Renewable Penetration (%)
14.69	51.54	3	-	-	3.14 M	2.74	71,899.79	2.31 M	100
14.69	60.86	-	508	-	3.18 M	2.78	78,539.91	2.27 M	81
14.69	60.86	-	-	508	3.18 M	2.78	78,539.91	2.27 M	81
14.66	59.02	1	508	-	3.21 M	2.80	73,617.45	2.35 M	88
14.66	59.02	1	-	508	3.21 M	2.80	73,617.45	2.35 M	88
14.69	60.86		508	508	3.31 M	2.89	73,602.64	2.46 M	81
14.66	59.02	1	508	508	3.33 M	2.91	68,680.18	2.54 M	88
-	62.51	1	508	-	3.35 M	2.93	87,834.02	2.33 M	70
-	62.51	1	-	508	3.35 M	2.93	87,834.02	2.33 M	70
-	62.51	-	508	-	3.35 M	2.93	95,611.17	2.24 M	58
-	62.51	-	-	508	3.35 M	2.93	95,611.17	2.24 M	58
14.69	-	1	508	-	3.39 M	2.96	116,172.00	2.05 M	30
14.69	-	1	-	508	3.39 M	2.96	116,172.00	2.05 M	30
-	62.51	1	508	508	3.48 M	3.04	82,896.74	2.52 M	70
-	62.51	-	508	508	3.48 M	3.04	90,673.91	2.43 M	58
9.79	-	-	508	-	3.48 M	3.04	132,518.60	1.94 M	7
9.79	-	-	-	508	3.48 M	3.04	132,518.60	1.94 M	7
14.69	-	1	508	508	3.52 M	3.07	111,234.70	2.23 M	30
-	-	4	508	-	3.60 M	3.14	113,915.80	2.28 M	38
-	-	4	-	508	3.60 M	3.14	113,915.80	2.28 M	38
9.79	-	-	508	508	3.60 M	3.15	127,581.40	2.13 M	7
-	-	4	508	508	3.72 M	3.25	108,978.60	2.46 M	38

Table 12. Third optimization with the 100 kW electrolyzer. Energy performance assessment of the alternatives in the target PLOCAN SmartGrid model.

55 kW PEMFC (kWh)	Genset 1 Energy Production (kWh/y)	Genset 2 Energy Production (kWh/y)	PV Rooftop 565 W Energy Production (kWh/y)	PV Wall 665 W Energy Production (kWh/y)	Wind Turbine Energy Production (kWh/y)	Lithium-Ion Battery Throughput (kWh/y)	Renewable Penetration (%)
4149	-	-	26,779	55,656	34,478	36,371	100
2166	78	18,963	26,779	65,722	-	55,187	81
2166	-	-	26,779	65,722	-	55,187	81
2881	47	11,639	26,779	63,740	11,493	48,210	88
2881	-	-	26,779	63,740	11,493	48,210	88
2166	78	18,963	26,779	65,722	-	55,187	81
2881	47	11,639	26,779	63,740	11,493	48,210	88
1498	117	30,122	-	67,502	11,493	55,050	70
1498	-	-	-	67,502	11,493	55,050	70
1301	157	41,272	-	67,502	-	62,496	58
1301	-	-	-	67,502	-	62,496	58
1394	210	68,752	26,779	-	11,493	66,879	30
1394	-	-	26,779	-	11,493	66,879	30
1498	117	30,122	-	67,502	11,493	55,050	70
1301	157	41,272	-	67,502	-	62,496	58
942	278	92,087	17,855	-	-	81,828	7
942	-	-	17,855	-	-	81,828	7
1394	210	68,752	38,500	-	11,493	66,879	30
1055	229	61,350	-	-	45,970	63,630	38
1055	-	-	-	-	45,970	63,630	38
942	278	92,087	25,667	-	-	81,828	7
1055	229	61,350	-	-	45,970	63,630	38

4.2. Analysis of the Alternative Scenarios

The first objective must be to meet the demand with 100% of renewable penetration. After the three described iterations developed in Section 4.1, only one alternative scenario meets this main objective, and this solution is described in Table 13.

Table 13. Optimized scenario for the target PLOCAN SmartGrid model.

PV Rooftop 565 W (kW)	PV Wall 665 W (kW)	Wind Turbines (nr)	Lithium-Ion Batteries (kW)	55 kW PEMFC (kW)	Electrolyzer (kW)	H_2 Tank (kg)	Renewable Penetration (%)
14.69	51.54	3	872	55	100	172.8	100

For a proper analysis, a technical, economic, and environmental comparison must be conducted under the current conditions of a system fully powered by fossil fuels. The main indicators of the current PLOCAN SmartGrid are presented in Table 2.

4.2.1. Technical Comparative Analysis of the Current and Target PLOCAN SmartGrid

Island-mode generation using diesel synchronous generators is a mature and reliable technology. It is important to note that installed generator sets have a combined generation capacity of 2 × 508 kW, which significantly exceeds the platform's baseline load demand. This configuration arises from the microgrid operating in island mode, without connection to the main grid, and therefore requires synchronous generation capacity equivalent to the maximum power allowed when prototypes are connected to the SmartGrid (4 × 250 kW), which typically involves asynchronous generation. This constrains leads to generator sets operating at less than 10% of their rated capacity almost continuously. From an operational perspective, such a low-load regime is suboptimal and can result in premature aging of the equipment due to issues such as soot accumulation on pistons, lubricant dilution, or excessive wear of cylinder liners [43].

From an energy mix perspective, a complete transformation occurs in offshore generation on the platform under study, achieving full renewable penetration through a generation mix composed of photovoltaic and wind energy, as illustrated in the comparative graph in Figure 9.

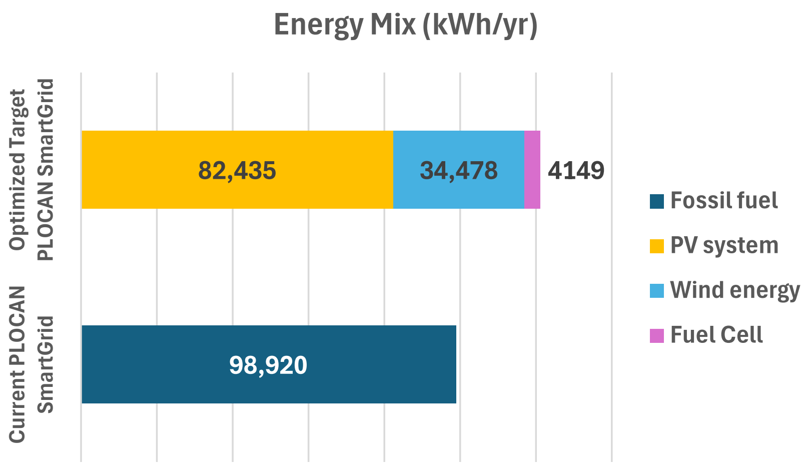

Figure 9. Energy mix comparative analysis.

Through the optimization of renewable energy sources, a surplus of 22.38% over the demand is achieved. This surplus is primarily directed to the electrolyzer, which consumes 16,371 kWh/year—equivalent to 73.94% of the total excess energy. The remaining surplus is lost due to the inefficiencies of the renewable generation inverters and lithium-ion batteries, representing 4.77% of the total annual energy generated and 26.06% of the surplus.

The global energy balance of the optimal alternative is presented in Figure 10. It is worth highlighting the performance of the power-to-grid pathway, where the overall efficiency of converting electricity into green hydrogen and subsequently reconverting it into electricity is 39.25%, a value consistent with those reported in the literature [44–46].

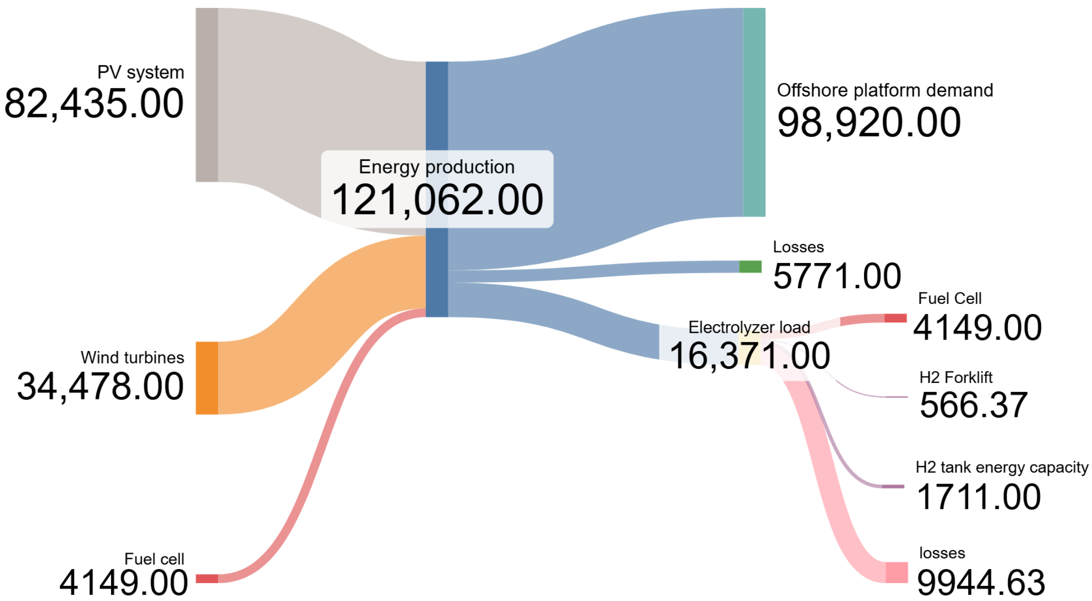

Figure 10. Sankey diagram of the energy balance of the optimized target PLOCAN SmartGrid.

Despite the efficiency limitations of the power-to-grid pathway, offshore green hydrogen production enables the complete decarbonization of the platform. Based on the optimized model of the target PLOCAN SmartGrid, all components related to green hydrogen were removed—namely, the 100 kW electrolyzer, the green hydrogen consumption, the fuel cell, and the hydrogen storage tank. The simulation results are presented in Tables 14 and 15.

Table 14. Fixed variables in the optimized target PLOCAN SmartGrid model without power-to-grid.

Lithium-Ion Batteries (kW)	PV Rooftop 565 W (kW)	PV Wall 665 W (kW)	Wind Turbines (nr)
872	<14.69	<62.51	<4

The 100 kW electrolyzer is clearly underutilized, with a capacity factor of only 1.87%. This outcome was expected, as previously discussed in Section 4.1.3, and is related to the oversizing required to maintain a capacity reserve in case the prototype slots are occupied.

For the activities carried out on the offshore platform and to ensure the stability of the isolated microgrid, it is necessary for the energy storage system to remain at or near its maximum capacity for a significant portion of the year. Figure 11 illustrates the hourly state of charge of the battery bank over a full calendar year, with an annual average state of charge reaching 72.90%.

Table 15. Energy performance assessment of the alternatives in the optimized target PLOCAN SmartGrid model without power-to-grid.

Genset 1 Energy Production (kWh/y)	Genset 2 Energy Production (kWh/y)	PV Rooftop 565 W Energy Production (kWh/y)	PV Wall 665 W Energy Production (kWh/y)	Wind Turbines Energy Production (kWh/y)	Lithium-Ion Battery Throughput (kWh/y)	Renewable Penetration (%)
21,639	-	26,779	60,623		56,450	78
8636	-	26,779	66,388	11,493	47,943	91
29,874	-	-	67,502	11,493	54,646	70
41,358	-	-	67,502	-	61,757	58
44,847	-	26,779	-	34,478	53,299	55
81,783	-	26,640	-	-	75,317	17
60,796	-	-	-	45,970	62,616	39
111,396	-	-	-	-	98,794	0

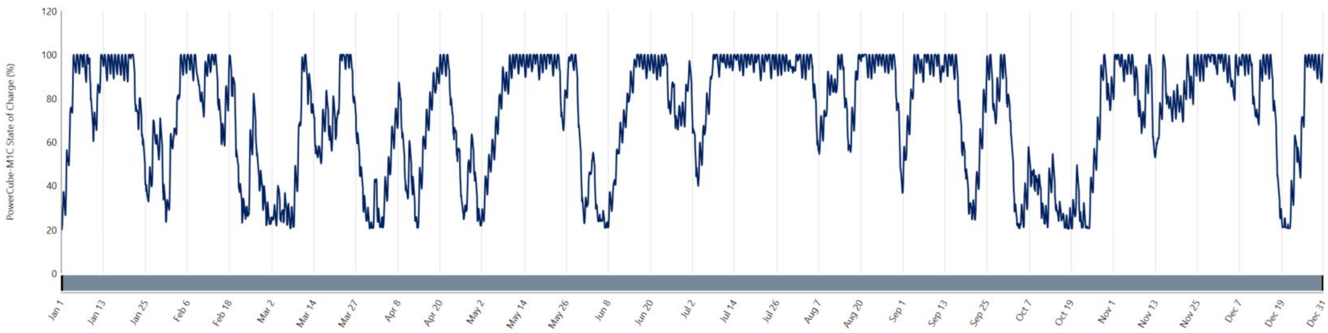

Figure 11. Annual electric storage state of charge.

4.2.2. Economic Comparative Analysis of the Current and Target PLOCAN SmartGrid

From an economic perspective, the optimized target PLOCAN SmartGrid scenario presents an NPC of EUR 3.14 million, whereas the current PLOCAN SmartGrid scenario—based solely on fossil fuels—results in an NPC of EUR 3.70 million. The difference between the two, and thus the economic savings of the target scenario, amounts to EUR 553,670. The difference between both scenarios lies in the distribution of costs over the 20-year project lifespan, as illustrated in Figure 12. In the baseline scenario, the largest share of expenses corresponds to OPEX, particularly fuel costs, which represent 58.77% of the total NPC. Annual diesel consumption reaches 85,308 L. Considering that the offshore platform's fuel tanks are refilled using 5000 L tankers, this results in approximately 17 refueling operations per year, or 340 over the 20-year operational period. In addition to the fuel cost itself, each refueling operation incurs significant expenses due to the maritime bunkering process.

Based on this improvement in NPC, a corresponding LCOE is obtained compared to the reference value (see Figure 13).

Under the specific conditions of the case study and in line with Refs. [19,42], the generation of green hydrogen and its application through the power-to-grid pathway enable 100% renewable energy penetration. This approach thus complements conventional electrical energy storage. However, from an economic analysis standpoint, it is relevant to introduce an alternative scenario—one in which no green hydrogen is produced, and consequently, the power-to-grid system is absent. In this case, all hydrogen-related equipment is removed. Although 100% renewable penetration is no longer achieved, one of the proposed solutions still reaches a 91% renewable share. More importantly, both the NPC and the LCOE in this scenario are significantly lower than those of the optimized solution described in Section 4.1.3 (see Table 16). These reductions are primarily due to the high capital costs associated with green hydrogen systems.

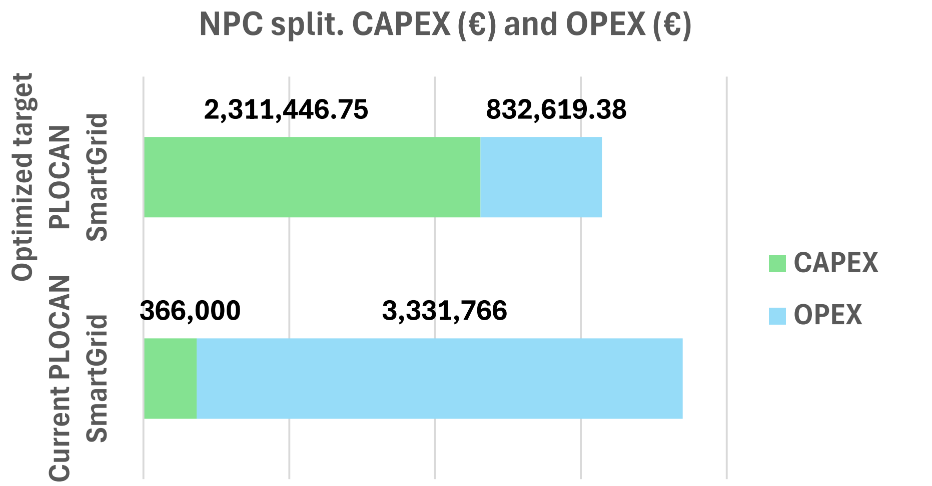

Figure 12. Comparative NPC split.

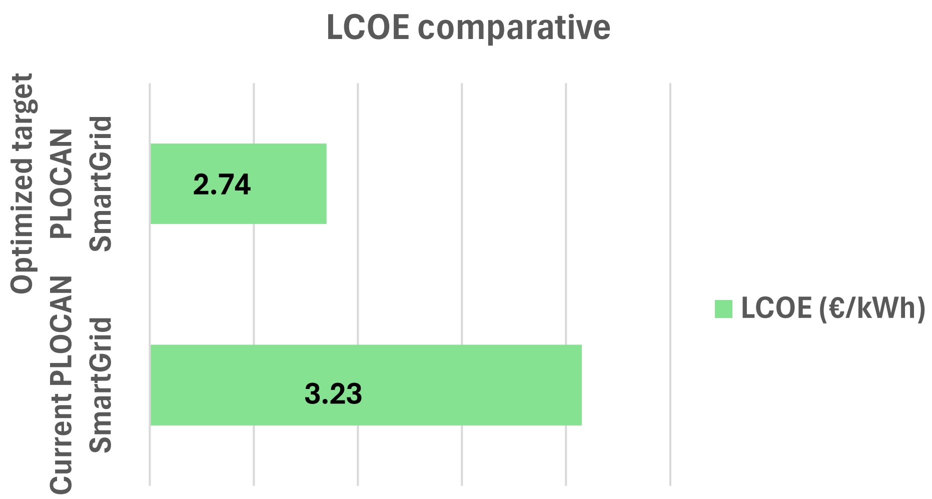

Figure 13. LCOE comparative.

Table 16. Economic assessment of the alternatives in the optimized target PLOCAN SmartGrid model. Comparison with and without power-to-grid.

	NPC (EUR)	LCOE (EUR/kWh)	OPEX (EUR/y)	CAPEX (EUR)	Renewable Penetration (%)
With power-to-grid	3.14 M	2.74	71,899.79	2.31 M	100
Without power-to-grid	1.58 M	1.38	17,793	1.38 M	91

4.2.3. Environmental Impact Comparative Analysis of the Current and Target PLOCAN SmartGrid

In the finalist alternative—the one that enables 100% renewable energy penetration—the emission of atmospheric pollutants resulting from electricity generation is, evidently, zero. In contrast, the emissions of polluting agents in the baseline scenario, represented by the current PLOCAN SmartGrid model, are those shown in Table 17.

Table 17. Pollutant emissions comparison. Current PLOCAN SmartGrid and optimized target PLOCAN SmartGrid.

	Current PLOCAN SmartGrid	Optimized Target PLOCAN SmartGrid
Fuel consumption (L/y)	85,308	0
CO_2 (kg/y)	225,424	0
CO (kg/y)	178	0
Unburned hydrocarbons (kg/y)	2.56	0
Particulate matter (kg/y)	5.12	0
SO_2 (kg/y)	560	0
NOx	1510	0

In addition to pollutant emissions, it is important to emphasize the environmental relevance of maritime bunkering operations involving up to 85,308 L of fuel annually. In the present case, the vessel responsible for this operation travels less than 10 nautical miles to reach the offshore platform for refueling. However, the 17 annual refueling operations still represent a potential environmental risk that, although controlled, should not be disregarded.

5. Discussions

The results of this study demonstrate that, based on the methodology applied in the case study, it is technically feasible to fully decarbonize an offshore platform using an optimized mix of renewable energies with specific energy storage. In line with Refs. [19,20], power-to-grid based on green H_2 is relevant to achieving this 100% renewable penetration, introducing the benefits of green H_2 as a long-term energy storage and complementing conventional battery storage and avoiding renewable curtailment.

All the investment costs used for the economic assessment are real costs, which are highly influenced by the relative additional costs of small-size projects, but especially for those additional costs related to the marinization of the equipment and the operations at sea, which were included in both CAPEX and OPEX. Consequently, achieving the 100% renewable scenario is technically feasible; however, it comes with important trade-offs, such as a high NPC and LCOE compared to scenarios with partial fossil backups. Despite this, the use of renewable energy, including green H_2, in the decarbonization of the offshore PLOCAN platform presents economic benefits compared to the reference system, which is fully fossil-dependent, due to the huge cost of fuel used throughout the lifetime of the system.

The results of the economic analysis cannot be compared to or validated against similar studies, as we are not aware of any previous research conducted at this scale and level of isolation in offshore locations. We do not consider that results obtained in onshore—although remote—isolated sites, such as in Refs. [47,48], are directly comparable. Assuming differences between our case study and the analyses conducted in the Faroe Islands [12], both studies acknowledge that, while offshore renewable energy and green hydrogen hold the potential to be more cost-effective in the long term, they entail substantial upfront capital expenditures. At PLOCAN, economic viability is achieved in the absence of subsidies, primarily due to the system's reduced scale, optimized design, and—most notably—the pre-existing offshore platform that serves as the structural base for the entire system, thereby eliminating the need for additional initial infrastructure investment. In contrast, the case in the Faroe Islands demonstrates that favorable outcomes are contingent upon active governmental intervention, given the higher complexity and capital intensity of the infrastructure involved.

This study aligns with the global trend of renewable microgrids [27]. While investment costs remain a limiting factor for complete decarbonization, future reductions in hydrogen technology costs may shift the balance, thanks mostly to the generalization of this already mature technology. Despite the economic barrier, we must highlight the opportunity that offshore renewable hydrogen generation represents, not only as a means for re-electrification, but also as a fuel or base for the manufacture of synthetic fuels that are key for the decarbonization of the economy.

Future works should include scaling to other offshore facilities and the integration of predictive control strategies based on artificial intelligence in order to export the methodology to other isolated systems. On the other hand, scaling the model will allow us to establish green H_2 costs that have not been evaluated in this article and determine strategies to achieve competitive prices based on renewable energy alternatives.

This study was based on the modelling of a real project prior to its final implementation. Further research should include the real validation of the proposed models, particularly the optimized solution.

6. Conclusions

This study demonstrates the technical and economic feasibility of fully decarbonizing offshore platforms and isolated microgrids by integrating renewable energy sources with hydrogen-based long-term storage. Through a tailored combination of photovoltaic panels, vertical-axis wind turbines, lithium-ion batteries, and green hydrogen systems, it is possible to achieve complete fossil fuel substitution and ensure reliable, autonomous operation.

Although fully renewable solutions maximize sustainability, the analysis also reveals that nearly full renewable scenarios may offer better economic viability under current technology and cost constraints. This balance between environmental ambition and financial feasibility outlines a pragmatic roadmap for the energy transition of offshore infrastructures. On the other hand, as highlighted in the discussion section, there are few references with which to compare the economic results.

The proposed methodology, combining resource characterization, demand profiling, and techno-economic optimization, provides a replicable framework adaptable to other remote maritime environments, supporting the development of autonomous, low-carbon energy systems that contribute to the blue economy.

However, the study has some limitations. The modelling is based on simulated operational data and does not yet incorporate maintenance schedules in offshore conditions or extreme weather events. In addition, the green hydrogen system was designed under conservative assumptions regarding electrolyzer efficiency, storage logistics, and fuel cell degradation, which could differ under real deployment.

Future work should include the empirical validation of the proposed system through on-site implementation and performance monitoring. Furthermore, extending the methodology to larger offshore platforms or floating structures, integrating predictive energy management strategies based on artificial intelligence, and analyzing the production of synthetic fuels from offshore green hydrogen represent promising avenues to consolidate sustainable and resilient offshore energy ecosystems.

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