

Article

Energy Storage and Management of Offshore Wind-Based Green Hydrogen Production

Isabella Pizzuti ^{1,*} , Michela Conti ² , Giovanni Delibra ¹ , Alessandro Corsini ¹  and Alessio Castorrini ¹

¹ Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, 00184 Rome, Italy; giovanni.delibra@uniroma1.it (G.D.); alessandro.corsini@uniroma1.it (A.C.); alessio.castorrini@uniroma1.it (A.C.)

² Department of Astronautical, Electrical and Energy Engineering, Sapienza University of Rome, 00184 Rome, Italy; michela.conti@uniroma1.it

* Correspondence: isabella.pizzuti@uniroma1.it

Abstract: The coupling of offshore wind energy with hydrogen production involves complex energy flow dynamics and management challenges. This study explores the production of hydrogen through a PEM electrolyzer powered by offshore wind farms and Lithium-ion batteries. A digital twin is developed in Python with the aim of supporting the sizing and carrying out a techno-economic analysis. A controller is designed to manage energy flows on an hourly basis. Three scenarios are analyzed by fixing the electrolyzer capacity to meet a steel plant's hydrogen demand while exploring different wind farm configurations where the electrolyzer capacity represents 40%, 60%, and 80% of the wind farm. The layout is optimized to account for the turbine wake. Results reveal that when the electrolyzer capacity is 80% of the wind farm, a better energy balance is achieved, with 87.5% of the wind production consumed by the electrolyzer. In all scenarios, the energy stored is less than 5%, highlighting its limitation as a storage solution in this application. LCOE and LCOH differ minimally between scenarios. Saved emissions from wind power reach 268 kton_{CO₂}/year while those from hydrogen production amount to 520 kton_{CO₂}/year, underlying the importance of hydrogen in hard-to-abate sectors.

Keywords: wind farm; hydrogen; battery



Academic Editor: Davide Papurello

Received: 4 February 2025

Revised: 18 February 2025

Accepted: 20 February 2025

Published: 24 February 2025

Citation: Pizzuti, I.; Conti, M.; Delibra, G.; Corsini, A.; Castorrini, A. Energy Storage and Management of Offshore Wind-Based Green Hydrogen Production. *Processes* **2025**, *13*, 643. <https://doi.org/10.3390/pr13030643>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The European goal of achieving carbon neutrality requires various renewable energies to be involved. Among them, hydrogen stands out as a promising solution due to its versatility across multiple applications. While different technologies are available for its production, electrolysis is one of the key methods for generating green hydrogen. However, for electrolysis to be truly green, the electricity used in the process must come from renewable energy sources. In 2023, global hydrogen production reached approximately 97 Mt, but less than 1% of the emissions were low, with around 1.4 GW produced through electrolysis, and only about 8% of the total production took place in Europe [1]. European targets by 2030 are, therefore, very ambitious, demanding the production of 10 Mt/year of green hydrogen. In Italy, the updated National Plan for Energy and Climate (PNIEC), renewed in 2024, plans around 0.25 Mt/year of hydrogen demand by 2030, 70% of which is to be produced in-house, which means a capacity of around 3 GW of electrolyzers. That hydrogen is mostly destined for transport and industry, in contrast with the current situation, where 95% is used in refineries and petrochemical industries and the last part for ammonia production. Another interesting application is steelmaking, where hydrogen can replace

coal as a reducing agent in integrated steel plants or as a replacement for natural gas in electric arc furnaces [2]. This makes hydrogen especially relevant for hard-to-abate sectors. Moreover, coupling renewable energy generation with hydrogen production emerges as a possible strategy for energy storage. Hydrogen acts both as an energy carrier and a storage system, complementing other storage technologies. This approach can be valuable in managing curtailment, which occurs when electricity generation overcomes the grid's capacity, resulting in energy waste as a measure to prevent congestion. In this context, green hydrogen production could mitigate the impact of renewable sources on the grid and reduce waste [3].

From this perspective, this work aims to develop a digital twin for the analysis and design of a coupled system that integrates offshore wind as a renewable source, a proton exchange membrane (PEM) electrolyzer to produce hydrogen, and a battery energy storage system (BESS). The system enables the integration of two energy vectors, electricity and hydrogen, through a controller developed in Python (V. 3.10) that manages energy flows among components and prioritizes hydrogen production. The digital twin is used to support the sizing of system components, ensuring optimal integration. The chosen configuration is a centralized onshore wind-to-hydrogen system, selected among the three models available in literature [4]: centralized onshore and offshore electrolysis and decentralized offshore electrolysis, depending on the location of the electrolysis system. In the first two configurations, the whole system is allocated on the shore and on an offshore platform, respectively. In contrast, in the decentralized configuration, a unique electrolyzer module is located on each turbine. The advantage of onshore configuration is that it allows the offshore wind farm to remain untouched, making it possible to design wind-to-hydrogen systems based on already planned or existing wind farms. Nevertheless, placing the electrolyzer offshore helps avoid some relevant costs associated with the wind farm's electric infrastructure and, consequently, reduces the cost of electricity, lowering the *lcoh* [5]. Currently, not many of these systems are operational, but the situation is growing and evolving towards offshore configurations. An example is the Sealhyfe project [6], which consists of a 1 MW PEM offshore electrolyzer powered by a 2 MW wind turbine. The project moved to the next phase, known as "HOPE" (Hydrogen Offshore Production for Europe), consisting of a 10 MW electrolyzer located offshore, close to the port of Ostend in Belgium [7]. Another project, "PosHydon", features a 1.25 MW PEM offshore electrolyzer to integrate three offshore technologies: hydrogen, wind, and gas [8].

Offshore wind farm projects planned in the Mediterranean Sea are progressively transitioning to floating foundation technologies due to the considerable depth of the seabed. Among the various floating platforms, the semi-submersible design has emerged as the most favored option, and it is commonly paired with wind turbines of the maximum size (15 MW) to optimize performance in these challenging conditions [9].

Different technologies for green hydrogen production are available, with alkaline technology covering around 60% of the global production and PEM electrolyzers accounting for 22% [1]. However, the trend in coupling electrolyzers and renewable energy is shifting toward PEM due to its rapid response to variable power input and short start-up times. Another advantage is the high operating pressure, which facilitates subsequent compression. While PEM electrolyzers are more expensive than alkalines, mainly due to the use of platinum catalysts [10], they are considered the preferred choice for coupling with renewable energy and achieving high-purity hydrogen [11].

The literature offers a wide range of studies addressing the modeling of wind-to-hydrogen systems from different perspectives. These include modeling of individual components and the entire system [12–18], system sizing [19–21], and energy management strategies [22–24]. Moreover, the modeling of alkaline electrolyzers has been extensively ex-

plored, with Ulleberg's semi-empirical model [12] being the most widely used. References for PEM electrolyzers are less abundant, but information can be found in [13–16]. Integrated system modeling has also been investigated in various studies. Egeland-Eriksen et al. [17] simulated a system on Simulink composed of a single 2.3 MW floating wind turbine connected to a PEM electrolyzer, a desalination system, a battery, and the grid, using real data from the Zephyros wind turbine. In a subsequent study [18], an entire wind park of 1.5 GW was considered and coupled with a PEM electrolyzer using wind data predicted through a polynomial regression model from the same real dataset of the Zephyros wind turbine. In terms of system sizing, Clua et al. [19] provided guidelines for sizing electrolyzers in grid-assisted wind-to-hydrogen systems operating at rated power. Deng et al. [20] explored sizing strategies based on hydrogen demand and different selling approaches. Finally, considering only the technical coupling of an offshore wind farm and an off-grid electrolyzer, Spyroudi et al. [21] recommended an electrolyzer capacity of 80% of the wind farm capacity. Different management strategies have been proposed to deal with such complex systems. Tebibel et al. [22] modeled a system composed of wind turbines, battery banks, water electrolyzers, power converters, and hydrogen tanks, developing a management strategy tailored to Algeria's prolonged low wind conditions. They applied this strategy while conducting multi-objective optimization to avoid the frequent shut-on and shut-off of the system. Liponi et al. [23] analyzed a system composed of a 1.5 MW turbine, an alkaline electrolyzer, and a battery in different scenarios, including partial grid support. In subsequent work [24], the system was scaled to a 39 MW wind farm coupled with multiple 1 MW alkaline electrolyzer modules divided into several groups. The developed strategy prioritized the electrolyzer, sending excess energy to the grid. The goal was to balance the operating hours of the groups and minimize transitions between on, off, and standby states. Additionally, Fei et al. [25] presented a coordinated energy management approach for a multi-energy ship microgrid, integrating power, hydrogen, and freshwater flows while considering operational constraints. Although applied to the maritime sector, this study reinforces the importance of comprehensive multi-energy coordination strategies, which are also relevant in offshore wind-based hydrogen production systems. Building on the insights from the literature review, this paper focuses on developing a control logic that effectively manages energy flows among the system's components, with particular attention paid to the role of the battery. Additionally, the study is enriched by the estimation of the wind farm's annual energy production (AEP) by optimizing the placement of individual turbines to maximize energy yield. These elements enable a comprehensive technical and economic assessment of the system. The analysis is based on hourly wind data extracted from the ERA5 (V. 5) reanalysis dataset. The control logic operates on an hourly basis, dynamically allocating the wind farm's power output between the electrolyzer and the battery. By applying this methodology to a case study in different scenarios, where the electrolyzer is sized to meet the hydrogen demand of the steel sector, the optimal sizes of these elements can be determined. As outputs, the technical, economic, and environmental performances are evaluated. The results show that sizing the electrolyzer at 80% of the wind farm capacity achieves the best energy performance. Furthermore, the battery has a minimal impact on the overall energy balance, making its contribution negligible.

The paper is organized as follows: the Section 1 details the specific models employed for each component, the control model, and the key performance indicators (KPIs) used for comparison. The Section 2 presents the case study, describing the three scenarios considered. Finally, the Section 3 discusses the results, followed by a concluding paragraph summarizing the main findings.

2. Materials and Methods

A digital model of the system, including a wind farm, electrolyzer, and batteries, was developed in Python (V. 3.10) to support the calculation of techno-economic performance. A scheme of the considered layout is showed in Figure 1. The development of the model is structured into the following main steps:

- Component modeling;
- Control logic design;
- Reconstruction of energy metabolism and performance calculation.

The wind farm was designed following the methodology described by [26]. A genetic optimization algorithm was applied to identify a wind farm layout that minimizes costs. The energy and economic performance were evaluated in three scenarios, each characterized by a different ratio between the capacity of the wind farm and that of the electrolyzer, with the latter kept constant. The objective was to identify the optimal size of the wind farm, given the fixed capacity of the electrolyzer based on the hydrogen demand. The simulation covered a period of one year, with an hourly resolution for the calculation of energy flows. In this initial phase, the focus was on assessing overall energy flows without accounting for the critical coupling challenges between the wind farm and the electrolyzer. Additionally, the analysis did not consider the energy consumption of auxiliary components like compressors or hydrogen storage flows. This allowed for a simplified evaluation of the main system dynamics before incorporating additional complexities.

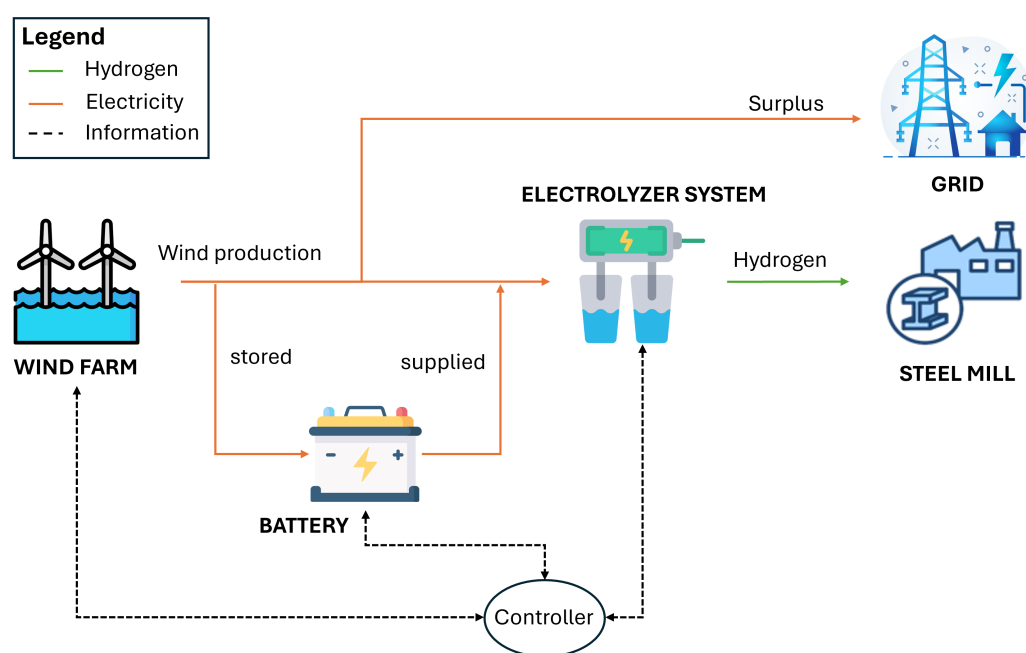


Figure 1. Schematic representation of the system.

2.1. Wind Farm Modeling

The wind farm design is based on a single-objective optimization approach, as described in a previous study [26]. The selected area for the wind farm is divided into a Cartesian grid of potential turbine positions, with minimum distance constraints between rotors. The wind distribution from the Global Wind Atlas (V. 3.0) [27] is modeled using the shape and scale parameters derived from Weibull distributions, which are used to construct the frequency of wind speeds and directions. To calculate the AEP and wake losses, the analytical Gauss–Curl hybrid model implemented in the FLORIS (V. 3.5) library [28] is utilized. This model is validated in several studies by comparing its results with SCADA

data [29,30]. A genetic algorithm based on NSGA [31] and implemented in Python (V. 3.10) using the Pymoo library (V. 0.6.1.3) [32] is employed to optimize the layout with a single objective: minimizing the levelized cost of energy (LCOE). The evaluation of the CAPital EXpenditures (CAPEX) and OPERational EXpenditures (OPEX) includes factors such as seabed depth, distance from the shore, and inter-array cable length.

2.2. Electrolyzer Modeling

The electrolyzer model is based on the technical datasheet of the electrolyzer, taking as inputs the power supplied by a renewable source P_{in} , as well as the operating temperature T and pressure P . It calculates the key performance metrics for a single module, including the hydrogen production rate $Prod$, the energy consumption $Cons$, and the water consumption rate $Cons_{wat}$. The parameters are the nominal power P_{nom} , the nominal production rate $Prod_{nom}$, the voltage stack V_{stack} , and the area of the membrane A .

Hydrogen production rate is calculated as follows [24]:

$$Prod = \frac{N_{cells} \cdot I_{cell}}{2F} \cdot \eta_f, \quad (1)$$

where N_{cells} is the number of cells inside a single stack, I_{cell} is the current of each cell in A, F is the Faraday constant equal to 96,485 C/mol, and η_f is the Faraday efficiency. The current of the cell is derived from the input power as follows:

$$I_{cell} = \frac{P_{in}}{V_{stack}}. \quad (2)$$

The number of cells, not always available in the literature, can be found through the inverse of Equation (1) using the nominal current obtained by the nominal power. Finally, for PEM electrolyzers, the Faraday efficiency can be found as follows [15]:

$$\eta_f = (a_1 \cdot p + a_2) \cdot \left(\frac{I_{cell}}{A} \right)^b + c. \quad (3)$$

This is an empirically derived model where the membrane area is in m^2 , and the coefficient values are -0.0034 , -0.001711 , -1 , and 1 for a_1 , a_2 , b , and c , respectively.

The electrolyzer consumption, $Cons$, is dynamically determined during operation by multiplying the power entering the electrolyzer by the duration of time:

$$Cons = P_{in} \cdot \text{timestep}. \quad (4)$$

Finally, the water consumption rate, $Cons_{wat}$, in kg/h is calculated considering that 15 kg of water are required to produce 1 kg of hydrogen [33].

2.3. Battery Modeling

The battery model simulates the behavior of a single module, as outlined in the technical datasheet, from which parameters such as the battery capacity $C_{battery}$, voltage V , minimum and maximum currents I_{min} and I_{max} , and the number of modules in series and parallel n_{series} and $n_{parallel}$ can be found. Meanwhile, the minimum and maximum state of charge SOC_{min} and SOC_{max} are expressed as a fraction of the battery capacity.

The behavior of the model depends on the sign of input power:

- When $P_{in} \geq 0$, the charging mode is activated;
- When $P_{in} < 0$, the discharging mode is activated.

First, the input energy is calculated by multiplying the power by the duration of time that is applied.

$$E_{in} = P_{in} \cdot \text{timestep}. \quad (5)$$

Secondly, the model applies an energy balance that considers the capacity and the limits of charge levels to determine the maximum energy that can be stored or withdrawn.

$$E_{cap_max} = \begin{cases} C_{battery} \cdot (SOC_{max} - SOC_{in}) & \text{if } P_{in} \geq 0 \\ C_{battery} \cdot (SOC_{in} - SOC_{min}) & \text{if } P_{in} < 0 \end{cases}. \quad (6)$$

The energy E that can be transferred or utilized, considering both the capacity limit (E_{cap_max}) and the availability of input energy (E_{in}), is calculated as follows:

$$E = \min(|E_{in}| - E_{cap_max}). \quad (7)$$

In this battery model, it is assumed that charging and discharging operations occur under the same current limits. A more detailed model could introduce different current limits for charging and discharging, considering that, in many real systems, the charging and discharging processes are not symmetrical. An additional control is implemented to meet the minimum and maximum current limits, considering the voltage applied to the battery. These parameters define the minimum energy required to activate the battery and the maximum energy that can be transferred during the timestep.

$$E_{min} = V \cdot I_{min} \cdot \text{timestep}, \quad (8)$$

$$E_{max} = V \cdot I_{max} \cdot \text{timestep}. \quad (9)$$

The energy exchanged with the battery is calculated as follows:

$$E_{battery} = \begin{cases} E_{max} & \text{if } E > E_{max} \\ E & \text{if } E_{min} \leq E \leq E_{max} \\ 0 & \text{if } E < E_{min} \end{cases}. \quad (10)$$

The exchanged energy is positive during charging, as energy is stored in the system. Conversely, during discharging, the exchanged energy is negative, as the battery releases energy to meet external demands.

The state of charge is updated according to the following:

$$SOC = \frac{C_{battery} \cdot SOC_{in} \pm E_{battery}}{C_{battery}}. \quad (11)$$

In charging mode, if the input energy exceeds the battery's charging capacity ($E_{battery}$), the additional energy cannot be stored and is identified as surplus:

$$E_{surplus} = \begin{cases} E_{in} - E_{battery} & \text{if } P_{in} \geq 0 \\ 0 & \text{if } P_{in} < 0 \end{cases}. \quad (12)$$

Conversely, in discharging mode, if the requested energy exceeds the energy the battery can supply, the difference is identified as a deficit:

$$E_{deficit} = \begin{cases} 0 & \text{if } P_{in} > 0 \\ |E_{in}| - E_{battery} & \text{if } P_{in} < 0 \end{cases}. \quad (13)$$

Finally, the model calculates the power output:

$$P_{\text{battery}} = \frac{E_{\text{battery}}}{\text{timestep}}, \quad (14)$$

$$P_{\text{surplus}} = \frac{E_{\text{surplus}}}{\text{timestep}}, \quad (15)$$

$$P_{\text{deficit}} = \frac{E_{\text{deficit}}}{\text{timestep}}. \quad (16)$$

The same model can be extended to handle multiple identical modules. Assuming n_{series} is the number of modules connected in series and n_{parallel} is the number of modules connected in parallel, the total capacity of the battery, the maximum and minimum current, and the voltage are calculated as follows:

$$\begin{aligned} C_{\text{battery}}^{\text{TOT}} &= C_{\text{battery}} \cdot n_{\text{series}} \cdot n_{\text{parallel}} \\ I_{\text{max}}^{\text{TOT}} &= I_{\text{max}} \cdot n_{\text{parallel}} \\ I_{\text{min}}^{\text{TOT}} &= I_{\text{min}} \cdot n_{\text{parallel}} \\ V^{\text{TOT}} &= V \cdot n_{\text{series}} \end{aligned} \quad (17)$$

2.4. Controller

A controller was designed in Python (V. 3.10) to manage the operation of wind turbines integrated with electrolyzers and a battery energy storage system. The controller is based on the following inputs and parameters:

- Inputs:
 - Power generated by the wind turbines (P_{WT}).
 - Initial state of charge in the battery (SOC_{in}).
- Parameters:
 - Maximum battery charge level (SOC_{max}).
 - Minimum power required to activate the electrolyzer (P_{min}).

Here, P_{min} is defined as a percentage of the nominal power P_{nom} . The controller first checks if the power generated by the wind turbines meets the electrolyzer's minimum activation power. Based on this check, the system operates under two main scenarios: surplus or deficit.

Surplus

A surplus occurs when the wind power is greater than the minimum power required to activate the electrolyzer. In this case, the controller proceeds with the following operations:

- a. *Activation:* The electrolyzer is turned on and is managed to adjust its power consumption to match the available wind power. Its operating range can vary from a minimum threshold up to its nominal capacity.
- b. *Surplus calculation:* Surplus is evaluated as the difference between wind power and the electrolyzer's consumption.
- c. *Surplus management:*
 - If the surplus is greater than zero, the controller checks the battery's state of charge.
 - If the battery is fully charged, the surplus is sent to the electrical grid.
 - Otherwise, the surplus is used to charge the battery.
- d. *Post-charge check:* After charging the battery, the controller checks again if there is still a surplus.
 - If the surplus persists, it is sent to the grid.

- Otherwise, balance is achieved with no exchanges with the grid.

Deficit

A deficit occurs when the wind power is insufficient to meet the minimum power required to activate the electrolyzer. In this case, the system adopts the following strategies:

- Power integration using the battery:*
 - The controller checks the battery's state of charge.
 - If the battery is not empty, the controller assesses whether combining wind power with battery power can ensure at least the electrolyzer's minimum operation.
 - If this condition is met, the battery supplies the necessary power. Otherwise, the electrolyzer remains off.
- Battery charging:*
 - If there is not enough power to activate the electrolyzer, the system attempts to use wind power to charge the battery.
 - If the battery is already full, the wind power is sent to the electrical grid.
 - Otherwise, after charging the battery, the system checks if there is any remaining power. If so, the energy is sent to the grid.

When multiple electrolyzers and batteries are present, the controller must adapt its logic to handle the increased complexity. In this case, the controller requires the number of electrolyzers connected in series and parallel as input. The power available from the wind turbines is first allocated to the electrolyzers operating in parallel. Within a parallel group, the total power is divided equally. Once the power requirements of the first series are met, the controller evaluates if there is enough surplus to activate the second series. In the case of positive a response, the second series of electrolyzers is activated. The controller prioritizes electrolyzers already in operation, ensuring they remain active before adding new ones.

2.5. Key Performance Indicators

The main key performance indicators (KPIs) used to compare the scenarios are outlined below. They allow for a comprehensive evaluation of both the technical and economic performance of the system.

- **Capacity factor (CF):** The wind farm CF is defined in Equation (18) as the ratio between the actual energy produced by the wind farm during the year and the nominal energy that could be produced. It is a measure of the efficiency of a wind farm in converting its theoretical maximum energy generation into actual output over a year.

$$CF = \frac{AEP}{N_T \cdot P_T \cdot T'} \quad (18)$$

where AEP is the annual energy production of the wind farm, N_T is the number of wind turbines, P_T is the nominal power of a single turbine, and T is the total number of hours in a year which equals 8760.

- **Utilization rate (UR):** The utilization rate of the electrolyzer is defined in Equation (19) as the ratio between actual and theoretical hydrogen production over a year. It represents how efficiently the electrolyzers are used compared to their theoretical maximum capacity, similar to the capacity factor (CF) but applied to electrolyzers.

$$UR = \frac{\sum_{t=1}^T \sum_{j=1}^{N_{EL}} Prod_{j,t}}{N_{EL} \cdot Prod_{nom} \cdot T'} \quad (19)$$

where $\text{Prod}_{j,t}$ is the hydrogen production of the j -th electrolyzer at timestep t . The actual production is calculated by summing over the entire period T and across all N_{EL} electrolyzers. The theoretical production is calculated as the product of the nominal production capacity Prod_{nom} of a single electrolyzer, the number of electrolyzers N_{EL} , and the total number of hours in a year T .

- $\text{Surplus\%}$ is calculated in Equation (20) as the ratio between the surplus energy from the wind farm over a year and the annual energy production (AEP).

$$\text{Surplus\%} = \frac{\int_0^T P_{\text{surplus}} dt}{\text{AEP}} \cdot 100. \quad (20)$$

- $\text{Cons\%}$ is calculated in Equation (21) as the ratio between the total energy consumption of all electrolyzers over a year and the annual energy production (AEP).

$$\text{Cons\%} = \frac{\sum_{t=1}^T \sum_{j=1}^{N_{\text{EL}}} \text{Cons}_{j,t}}{\text{AEP}} \cdot 100, \quad (21)$$

where $\text{Cons}_{j,t}$ is the energy consumption of the j -th electrolyzer at timestep t . The total energy consumed by all electrolyzers is calculated as the sum over the entire period T and across all N_{EL} electrolyzers.

- $\text{Stored\%}$ is calculated in Equation (22) as the ratio between the energy stored in the battery over a year and the annual energy production (AEP).

$$\text{Stored\%} = \frac{\int_0^T P_{\text{battery}}^+ dt}{\text{AEP}} \cdot 100, \quad (22)$$

where P_{battery}^+ is the positive component of the power flowing into the battery, representing the energy being stored at each timestep.

- Levelized cost of energy (LCOE): The LCOE is defined as the ratio between the total costs and the annual energy production of the wind farm. It is a measure of the cost of the power plant during its lifetime.

$$\text{LCOE} = \frac{\text{CAPEX}_{\text{WF}} + \sum_{y=1}^{\text{LT}} \frac{\text{OPEX}_{\text{WF},y}}{(1+r)^y}}{\sum_{y=1}^{\text{LT}} \frac{\text{AEP}_y}{(1+r)^y}}, \quad (23)$$

where LT is the plant lifetime, CAPEX_{WF} and OPEX_{WF} are the capex and opex of the wind farm, and r is the discount rate.

- The levelized cost of hydrogen LCOH [10] represents the cost for the entire system, including the electricity cost per kg of hydrogen produced.

$$\text{LCOH} = \frac{\text{CAPEX}_{\text{El}} + \sum_{y=1}^{\text{LT}} \frac{\text{OPEX}_{\text{El}} + \text{LCOE} \cdot E_{\text{in}}}{(1+r)^y}}{\sum_{y=1}^{\text{LT}} \frac{\text{Prod}_y}{(1+r)^y}}, \quad (24)$$

where CAPEX_{El} and OPEX_{El} are the costs of the electrolyzer, the latter also includes the cost of electrolyzer replacement and the cost for freshwater purchase.

- Net present value (NPV):

$$\text{NPV} = \sum_{y=1}^{\text{LT}} \frac{\text{OPEX}_y + \text{Revenues}_y}{(1+i)^y} - \text{CAPEX}. \quad (25)$$

Here,

$$\text{CAPEX} = \text{CAPEX}_{\text{WT}} + \text{CAPEX}_{\text{El}} + \text{CAPEX}_{\text{BESS}}, \quad (26)$$

where $CAPEX_{BESS}$ is the CAPEX of battery storage, and Revenues is the total income derived from surplus electricity sold to the grid and hydrogen sold to the steel plant.

- Payback period (PBP):

$$PBP = \frac{CAPEX}{NPV}. \quad (27)$$

- Saved emissions from wind energy production (α):

$$\alpha = c_1 \cdot MWh_{el}, \quad (28)$$

where MWh_{el} represents the total production of electricity by wind turbines. c_1 is the CO_2 emissions associated with producing 1 MWh of electricity from the national grid, considering the current technological mix which, for Italy, is equal to $0.40 \text{ ton}_{CO_2eq}/MWh$ [34].

- Saved emissions from hydrogen production (β):

$$\beta = c_2 \cdot f_{H_2-Steel} \cdot \sum_{t=1}^T \sum_{j=1}^{N_{EL}} Prod_{j,t}, \quad (29)$$

where c_2 is the CO_2 emissions associated with producing one ton of steel from traditional processes equal to $2 \text{ tons}_{CO_2}/\text{ton}_{Steel}$ [35], and $f_{H_2-Steel}$ is the conversion factor representing the amount of steel (in tons) produced per kg of hydrogen consumed, equal to $1/60 \text{ ton}_{Steel}/\text{kg}_{H_2}$ [36]. The total hydrogen production is calculated by summing over the entire period T and across all N_{EL} electrolyzers.

3. Case Study

The outlined methodology is used in a virtual case study featuring an offshore wind farm situated in Sicily, in the Mediterranean Sea, 30 km off the coast of Marsala. The wind farm covers an area of $9 \times 10 \text{ km}$ and is characterized by a mean wind speed at hub height of 7.02 m/s and a mean water depth of 340 m . The wind increase and bathymetry data for layout optimization are downloaded from the Global Wind Atlas (V. 3.0) [27], while hourly wind data are sourced from the Copernicus ERA5 Dataset (V. 5) [37]. The ambient turbulence intensity is assumed based on the FINO1 experiment [38]. Given the mean wind speed of the location, the selected turbine is the IEA 15 MW [39], whose parameters are indicated in Table 1.

Table 1. Component characteristics.

Component	Parameter	Value
WIND TURBINE	Rated power (MW)	15
	Cut-in wind speed (m/s)	3
	Cut-off wind speed (m/s)	15
	Rated wind speed (m/s)	10
BESS—single module	Capacity (kWh)	344
	Voltage range (V)	1075.2–1363.2
	Rated voltage (V)	1228.8
	SOC_{min}	0.2
	SOC_{max}	1
	I_{min} (A)	126
	I_{max} (A)	156

Table 1. *Cont.*

Component	Parameter	Value
PEM	Rated power (MW)	2.5
	Nominal production rate (kg/h)	44.22
	Delivery pressure (barg)	30
	Operative temperature (°C)	80
	Stack voltage (kV)	30
	Membrane area (cm ²)	100

The chosen battery is a lithium iron phosphate battery, typically used for industrial applications, because of its thermal stability, high energy density, and long life cycle. The values of the main parameters are listed in Table 1.

The electrolysis system is situated onshore and consists of multiple 2.5 MW modules [40], with the parameters listed in Table 1. The expected lifetime of the plant (LT) is 20 years [41].

Starting from steel demand, assumed for a typical steel plant as 500,000 tons/year with a conversion rate of 60 kg of hydrogen per ton of steel [36], the consequent hydrogen demand of 30,000 tons/year is obtained. With the nominal production rate and power of the single module already defined and an assumed utilization factor of around 63%, the required electrolysis capacity is approximately 160 MW, corresponding to 64 modules distributed equally in series and parallel configurations. Fixing this capacity, three cases are built to determine the best capacity ratio between the hydrogen plant and the wind farm, varying the latter. In particular, the electrolyzer's capacity is set as 40%, 60%, and 80% of that of the wind farm. The goal is to ensure the electrolyzer operates continuously, requiring a larger wind farm to mitigate fluctuations in wind power. These values represent a balanced distribution across the range and are chosen to explore different trade-offs: the first scenario prioritizes hydrogen production, the last one minimizes surplus energy, and the intermediate case balances both aspects. The BESS capacity is assumed to be 40% of that of the wind farm. The resulting components' number of turbines and BESS modules required are summarized in Table 2.

Table 2. Key variables for each scenario.

Key Variable	Scenario A	Scenario B	Scenario C
Electrolyzer capacity (MW)	160	160	160
Number of PEM modules	64	64	64
Wind farm capacity (MW)	208	278	416
Number of turbines	14	19	28
BESS capacity (MWh)	83	111	166
Number of BESS modules	242	323	484

Regarding the economic performance of the system, in order to compute the KPI defined in the methodology section, the CAPEX and OPEX of all components are calculated. For the OWE, the economic model illustrated in [26] is employed. This model includes all cost components specific to the wind farm, such as wind turbines, platforms, mooring, electrical infrastructure, and installation, as well as development and consent costs, which encompass project expenses, environmental surveys, and seabed and climate analyses. Meanwhile, for the BESS and PEM components, the values in Table 3 are used. For the computation of the NPV and PBP, the pun is assumed to be EUR 130/MWh, and the hydrogen price is EUR 4.50/kg of hydrogen sold. The incentives for wind electricity sold

to the grid are EUR 185/MWh, as defined in the FER II decree [42], while incentives for hydrogen production are assumed to be EUR 4/kg. The discount rate is 5%.

Table 3. Economic parameters.

Parameter	Value	Reference
$CAPEX_{WF}$	-	[26]
$OPEX_{WF}$	-	[26]
$CAPEX_{BESS}$	EUR 522.27/kWh	[43]
$OPEX_{BESS}$	EUR 9.51/kW/year + 2.91 cEUR/kWh/year	[43]
$CAPEX_{EI}$	EUR 723/kW	[4,33,44]
$OPEX_{EI}$	EUR 18.49/kW/year	[10,33,44]
PEM replacement cost	12% $CAPEX_{EI}$	[33]
Year of replacement	11	[10]
Freshwater cost	EUR 2/m ³	[45]
Plant lifetime	20 years	[41]

4. Results

4.1. Technical Results

Optimized layouts

The optimized layouts obtained through the layout optimization framework in the three scenarios are illustrated in Figure 2, where the x and y axes are reported as the x and y coordinates of the turbines.

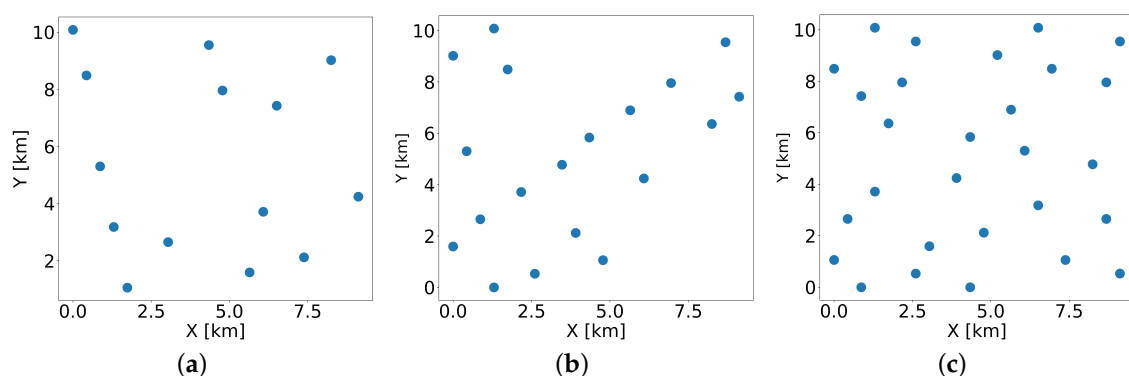


Figure 2. Wind farm optimized layout in the three scenarios: scenario A (a), scenario B (b), and scenario C (c).

They are characterized by the capacity factor and AEP values listed in Tables 4 and 5. AEP increases when the wind farm size is increased, but not linearly. This happens because increasing the turbine number does not imply a proportional increase in energy production due to the different distribution of turbines and, therefore, a different wake interaction among them. The capacity factor slightly decreases, indicating that in the third scenario, the resource is less exploited than in the first two.

Electricity

The annual energy production of the offshore wind farm in the three scenarios is illustrated in Figure 3, along with the main components of energy distribution. These components include (i) the energy used for hydrogen production via the electrolyzer, (ii) the energy stored in the battery, and (iii) the surplus fed to the grid. While wind AEP doubles from Scenario A to Scenario C, the electrolyzer's energy consumption increases by

27%, highlighting that simply increasing the size of the wind farm does not correspond to a proportional increase in hydrogen production, as the electrolyzer's capacity acts as a limiting factor. The amount of energy stored in the battery system is always below 5% of AEP in all scenarios, indicating that the battery plays a minor role in energy balancing. The main difference across scenarios lies in the amount of surplus, which increases six times in Scenario C compared to Scenario A, rising from 100 GWh to 671 GWh. The surplus is an indicator of the balance between the power system and the electrical grid. In a context where the electrolyzer size is fixed by hydrogen demand, a suitable sizing criterion for the wind farm could be to find a balance between PEM consumption and electricity surplus. Based on this criterion, Scenario A proves to be the most energy-efficient choice, ensuring the highest utilization of the wind energy since only 12.5% is injected into the grid.

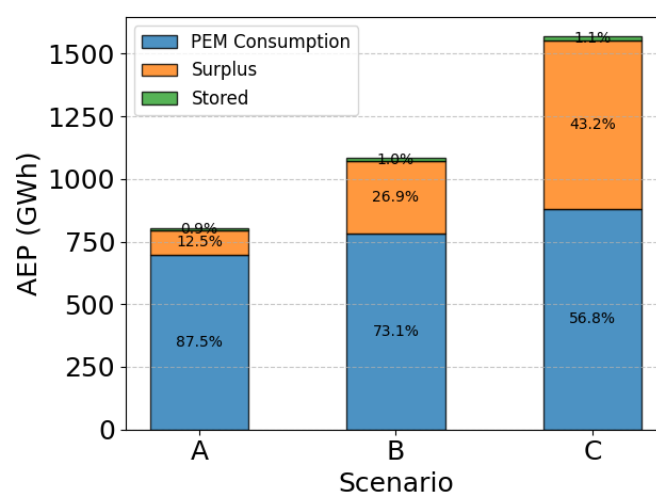


Figure 3. Energy balance in the three scenarios over one year.

Since Scenario A stands out as the most efficient from an energetic perspective, an overview of the system's yearly performance is offered in Figure 4. The monthly wind production fluctuates throughout the year, with the highest production (above 80 MWh) observed in March, November, and December. The majority of energy is consumed (blue bars), while surplus (orange) and stored energy (green) remain relatively small across all months. More than 80% of wind production is consumed by the electrolyzer, while the surplus energy is fed into the grid, and even when analyzing monthly flows, the battery plays a negligible role.

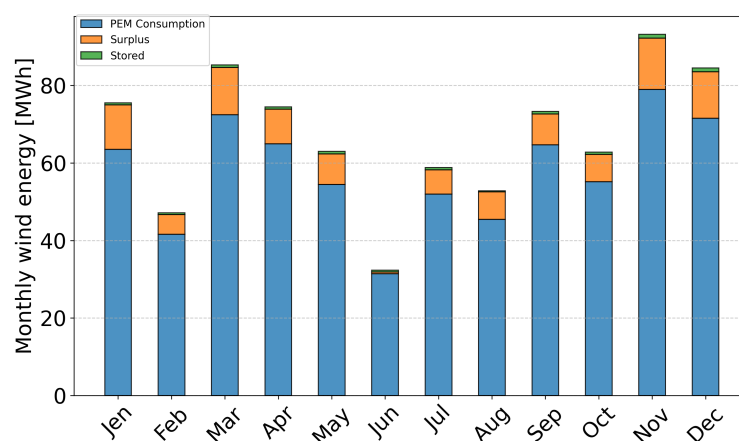


Figure 4. Monthly energy balance of Scenario A over one year.

To explore the system dynamics in greater detail, Figure 5 presents the hourly power profiles of Scenario A for one representative week per season. During winter and autumn, wind production frequently reaches peak values. Consequently, the electrolyzer (PEM consumption) operates close to its nominal capacity. Surplus is used to charge the battery, contributing to the power supply for less than 2 h when activated. During spring, the behavior is similar, with the difference that wind production exhibits greater fluctuations. The electrolyzer operates at a varying power, deviating from its nominal capacity at certain times. With a storage capacity of 83 MWh, the battery can sustain the 160 MW electrolyzer for only a few hours when fully charged, making it ineffective as a long-term buffering solution. During summer, wind production is lower than in other seasons, and the battery is never activated due to the lack of surplus. This indicates that the battery's role is highly dependent on excess wind generation. In periods of low production, it remains inactive, further emphasizing its limited contribution to overall system balancing. This behavior is a direct result of the control logic, which prioritizes the electrolyzer at all times. Although alternative control strategies could be explored, such as prioritizing battery charging during specific hours of the day, this approach results in energy losses and is not feasible unless the battery size is increased to sustain the electrolyzer for a longer duration.

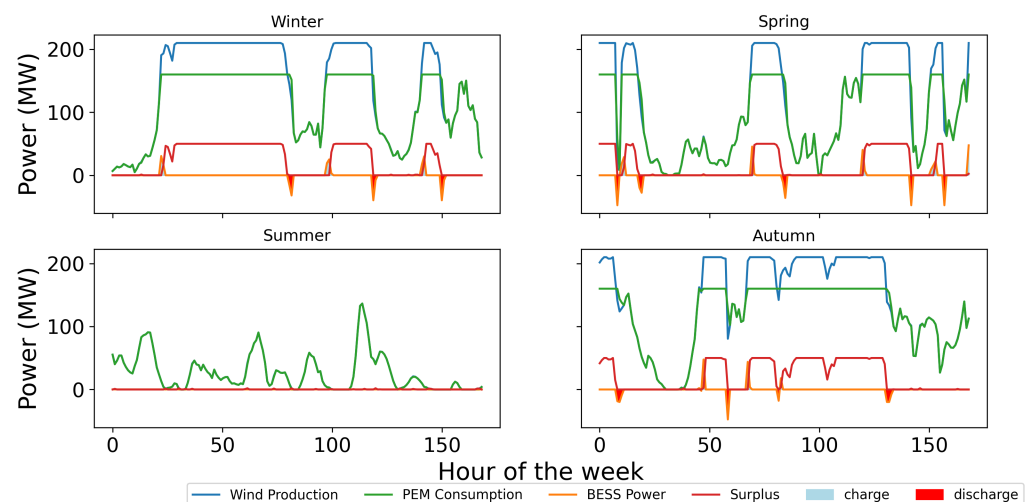


Figure 5. Seasonal power profiles in Scenario A over four representative weeks.

The state of charge (SoC) of the battery throughout the week for each season is illustrated in Figure 6. In Winter, Spring, and Autumn, the SOC fluctuates between full charge (SOC = 1.0) and minimum charge (SOC = 0.4), but the charging/discharging periods are brief and inconsistent. The battery is only used sporadically for balancing short-term energy fluctuations rather than sustained storage. Furthermore, the battery reaches full charge but is quickly discharged, reinforcing its limited capacity and role. In Summer, SOC remains constant at the minimum level (around 0.4), indicating that the battery is not used. The battery never drops below a SOC of 0.4 because, at this level, the remaining energy is insufficient to power all eight electrolyzer modules in parallel simultaneously.

Hydrogen Production

As shown in Table 4, annual hydrogen production increases from Scenario A to C, rising from 12 to 16 kton, despite having the same installed electrolyzer capacity. This is due to the greater availability of wind energy. Consequently, the utilization rate also increases slightly, from 49.68% to 62.85%.

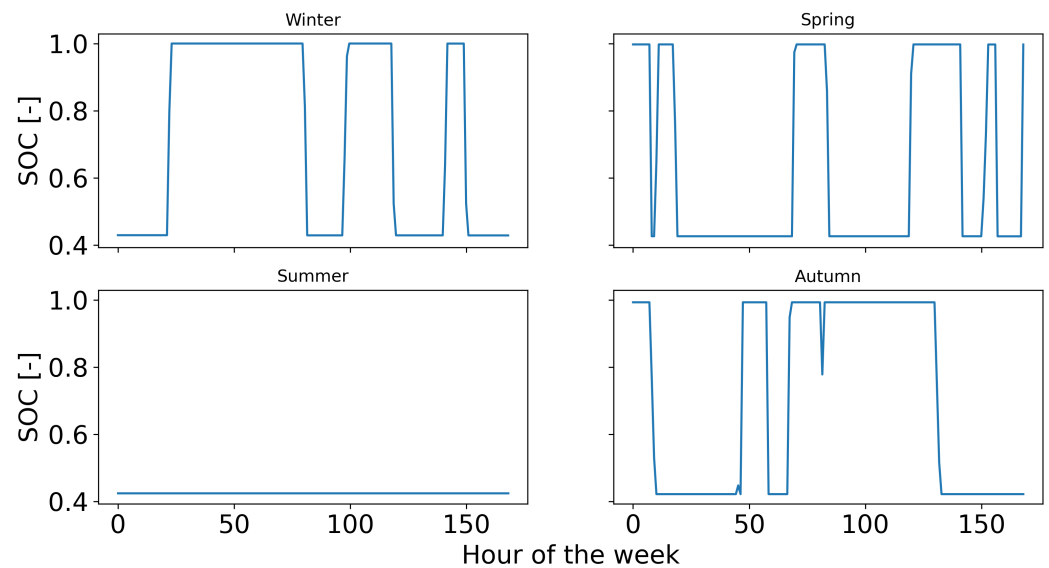


Figure 6. Seasonal SOC trend in Scenario A over four representative weeks.

Figure 7 illustrates the monthly hydrogen production throughout the year for the three scenarios, along with the coverage. The coverage is defined as the ratio between the average monthly production across the three scenarios and the average demand, representing the system's ability to meet the hydrogen demand.

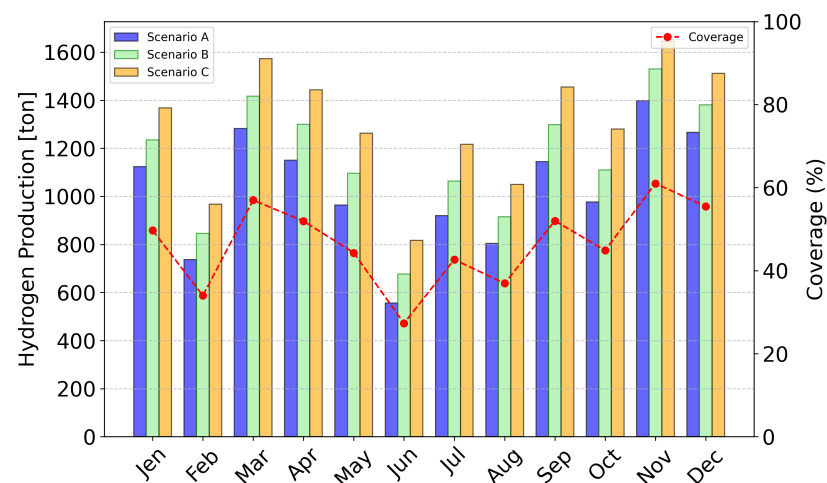


Figure 7. Monthly hydrogen production in the three scenarios and coverage percentage (red line) over one year.

From this perspective, the electrolyzer meets, on average, between 30% and 70% of the annual hydrogen demand, showing a considerable variation. Meanwhile, the monthly hydrogen production trend aligns with the overall annual trend.

Further details of annual energy flows and KPIs are provided in Tables 4 and 5.

Table 4. Technical results of the three scenarios for each vector

Vector	Parameter	Scenario A	Scenario B	Scenario C
ELECTRICITY	Wind AEP (GWh)	776	1046	1522
	Stored energy (GWh)	7	11	17
	PEM consumption (GWh)	696	784	881
	Surplus (GWh)	100	288	671
HYDROGEN	H ₂ production (kton)	12	14	16

Table 5. Comparison of the technical KPI in the three scenarios

Parameter	Scenario A	Scenario B	Scenario C
CF _%	43.27	42.92	42.17
Stored _%	0.9	1.0	1.1
Cons _%	87.5	73.1	56.8
Surplus _%	12.5	26.9	43.2
UR _%	49.68	55.90	62.85

4.2. Economic Results

Table 6 lists the CAPEX and OPEX of the entire system, including the relative share of each component, expressed as a percentage of the total, along with the remaining economic KPIs described in the relative section.

Table 6. Economic results in the three scenarios.

Parameter	Share	Scenario A	Scenario B	Scenario C
CAPEX (MEUR)		783	957	1394
	Wind farm _%	80	82	85
	BESS _%	6	6	6
	PEM _%	15	12	8
OPEX (MEUR/year)		1.6	2.1	2.9
	Wind farm _%	88	90	92
	BESS _%	3	3	3
	PEM _%	9	5	5
LCOE (EUR/MWh)		98.24	94.93	97.19
LCOH (EUR/kg)		6.69	6.57	6.46
NPV (MEUR)		490	1017	1908
PBP (years)		8	6	5

Increasing the size of the wind farm, which always represents the primary cost component of the system, leads to higher costs in terms of both CAPEX and OPEX. The BESS storage remains the least expensive component, with its costs remaining constant across all scenarios. On the other hand, since the electrolyzer size is unchanged across the scenarios, its share of both CAPEX and OPEX decreases as the wind farm size increases.

Regarding KPIs, the LCOE does not increase linearly from Scenario A to Scenario C due to the non-linear increase in costs. That, combined with the trend of AEP, results in a decrease in LCOE for Scenario B, followed by an increase in Scenario C. Consequently, from an economic perspective, the wind farm in Scenario B is the most advantageous due to its lower LCOE. A similar trend is observed for the LCOH, which remains relatively stable but still positions Scenario B as the most favorable.

However, when evaluating economic feasibility in terms of NPV and PBP, Scenario C emerges as the optimal choice, offering a higher NPV and a lower PBP. This is because the revenues from hydrogen sales, despite the modest increase in hydrogen production in Scenario C, do not rise significantly, increasing from 1042 MEUR in Scenario A to 1318 MEUR in Scenario C. Instead, the greater surplus energy in Scenario C allows for more electricity to be sold to the grid, generating additional revenues despite the higher initial investment. In fact, revenues from surplus energy sold to the grid increase from 195 MEUR in Scenario A to 1310 MEUR in Scenario C.

From an overall perspective, given the minimal differences in LCOH, Scenario C emerges as the most advantageous option.

4.3. Environmental Results

The environmental KPIs obtained are summarized in Table 7. These results show that Scenario C is the most effective, achieving a six-fold increase in emission savings from energy surplus sales compared to Scenario A. This outcome is expected, as Scenario C features a larger wind farm with a fixed electrolyzer and more surplus energy available for grid sales.

The emissions avoided through hydrogen sales also increase in Scenario C, but to a lesser extent, increasing from 411 kt_{CO₂}/year to 520 kt_{CO₂}/year. This is because the increase in hydrogen production is relatively modest compared to the rise in surplus energy.

However, when comparing the emissions savings from surplus energy sales and hydrogen sales, it becomes evident that the emissions avoided through surplus energy sales are significantly lower than those avoided through hydrogen use. This highlights that using hydrogen in hard-to-abate sectors could play a crucial role in reducing CO₂ emissions.

Table 7. Environmental results in the three scenarios.

Parameter	Scenario A	Scenario B	Scenario C
Saved emissions production from WT (α) kt _{CO₂} /year	40	115	268
Saved emissions production from H ₂ (β) kt _{CO₂} /year	411	462	520

5. Conclusions

In this study, a digital twin was developed in Python (V. 3.10) to analyze the coupling between offshore wind production, battery storage, and electrolyzers for hydrogen production. A control logic was designed to prioritize hydrogen production. The offshore wind farm was modeled based on a previous study, optimizing the layout while accounting for wake effects using an NSGA optimization algorithm from the Pymoo library (V. 0.6.1.3). The electrolyzer and BESS models were developed using technical datasheets. Economic and environmental performance indicators for the overall system were also evaluated.

Three scenarios were analyzed based on the hydrogen demand of a steel plant requiring 500,000 tons/year of hydrogen. To meet this demand, a 160 MW electrolyzer was selected. The wind farm capacity was obtained considering the electrolyzer capacity to be 40%, 60%, and 80% of the wind farm size, while the battery capacity was set at 40% of the wind farm capacity. Key findings from the results include the following:

- The amount of energy stored in the battery system is always below 5% of the AEP in all scenarios, highlighting its limited role in energy balancing. Despite the battery capacity of 83 MWh, its contribution appears negligible. This is not due to the control logic, as even prioritizing the battery for specific hours would not increase its impact. The battery would discharge within a few hours, adding energy losses without significantly improving system performance.
- Scenario A exhibits the best energy balance, as sizing the electrolyzer at 80% of the wind farm capacity minimizes surplus energy and maximizes wind energy utilization for hydrogen production;
- However, the largest hydrogen production occurs in Scenario C, which benefits from the greatest available wind energy;

- All three scenarios present similar values of LCOE and LCOH. However, Scenario C demonstrates the highest net present value (NPV) and the shortest payback period (PBP), making it the most attractive investment;
- From an environmental perspective, Scenario C is the most favorable due to its higher wind energy generation and hydrogen production.

The overall analysis suggests that sizing the electrolyzer at 80% of the wind farm capacity (Scenario A) achieves the best energy performance, although it results in lower profitability compared to other scenarios. Nonetheless, this configuration minimizes surplus energy, making it potentially the best choice for offshore electrolyzer placement.

In contrast, Scenario C generates a higher surplus, leading to greater revenues not only from hydrogen sales but also from electricity sales. This makes Scenario C an optimal choice, particularly when the electrolyzer is located onshore.

Author Contributions: Conceptualization, I.P., M.C. and A.C. (Alessio Castorrini); Data curation, I.P. and M.C.; Formal analysis, I.P.; Funding acquisition, G.D. and A.C. (Alessandro Corsini); Investigation, M.C.; Methodology, I.P., M.C. and A.C. (Alessio Castorrini); Project administration, G.D.; Resources, M.C.; Software, I.P. and M.C.; Supervision, A.C. (Alessandro Corsini) and A.C. (Alessio Castorrini); Validation, I.P. and M.C.; Visualization, I.P.; Writing—original draft, I.P. and M.C.; Writing—review and editing, G.D., A.C. (Alessandro Corsini) and A.C. (Alessio Castorrini). All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Italian Ministry of University and Research (MUR) as part of the EU programme NextGenerationEU, PNRR-M4C2-PE0000021 “NEST-Network 4 Energy Sustainable Transition” in Spoke 2 “Energy Harvesting and offshore renewables” and by Regione Lazio under agreement with the Department of Mechanical and Aerospace Engineering of Sapienza University of Rome on research and support to Renewable Energy Communities.

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 conflicts of interest.

Nomenclature

Acronyms

AEP	Annual Energy Production
BESS	Battery Energy Storage System
CAPEX	CAPital EXpenditures
CF	Capacity Factor
FLORIS	FLOw Redirection and Induction in Steady State
KPI	Key Performance Indicators
LCOE	Levelized Cost of Electricity
LCOH	Levelized Cost of Hydrogen
NPV	Net Present Value
NSGA	Non-Dominated Sorting Genetic Algorithm
OPEX	OPerational EXpenditures
PBP	Pay Back Period
PEM	Proton Exchange Membrane
SCADA	Supervisory Control and Data Acquisition
SOC	State of Charge
UR	Utilization Rate
WT	Wind Turbine

Parameters

α	Saved emissions from wind energy production [$\text{tonCO}_2/\text{year}$]
β	Saved emissions from hydrogen production [$\text{tonCO}_2/\text{year}$]
η_f	Faraday efficiency
A	Membrane area of the electrolyzer [m^2]
a_1	Coefficient for faraday efficiency computation
a_2	Coefficient for faraday efficiency computation
c	Coefficient for faraday efficiency computation
c_1	Emissions factor for electricity production [$\text{tonCO}_2/\text{MWh}$]
c_2	Emissions factor for steel production [$\text{tonCO}_2/\text{ton}_{\text{steel}}$]
Cons	Energy consumed by electrolyzer [kWh]
C_{battery}	Battery capacity [kWh]
Cons_{wat}	Water consumed by electrolyzer [kg/h]
E	Energy [kWh]
$f_{\text{H}_2-\text{Steel}}$	Conversion factor steel-hydrogen [$\text{ton}_{\text{Steel}}/\text{kg}_{\text{H}_2}$]
F	Faraday constant [C/mol]
I	Current [A]
LT	Lifetime of the plant [years]
N_{cells}	Number of cells inside a stack
N_{EL}	Number of electrolyzer modules
N_{T}	Number of turbines
P	Power [kW]
p	Pressure [bar]
Prod	Hydrogen production rate [kg/h]
r	Discount rate
T	Number of hours in one year
timestep	Time interval [h]
V	Voltage [V]

References

1. International Energy Agency (IEA). Global Hydrogen Review 2024. Available online: <https://www.iea.org/reports/global-hydrogen-review-2024> (accessed on 19 February 2025).
2. Ministero Delle Imprese e Del Made in Italy (MIMIT). Strategia Nazionale Idrogeno. 2024. Available online: <https://www.mimit.gov.it/index.php/it/notizie-stampa/avviata-la-consultazione-pubblica-della-strategia-nazionale-sull-idrogeno> (accessed on 19 February 2025).
3. Terna S.P.A. e gruppo Terna. Contesto ed Evoluzione Del Sistema Elettrico. 2019. Available online: <https://www.terna.it/it/sistema-elettrico/ruolo-terna/insight> (accessed on 19 February 2025).
4. Ibrahim, O.S.; Singlitico, A.; Proskovics, R.; McDonagh, S.; Desmond, C.; Murphy, J.D. Dedicated large-scale floating offshore wind to hydrogen: Assessing design variables in proposed typologies. *Renew. Sustain. Energy Rev.* **2022**, *160*, 112310. [CrossRef]
5. Singlitico, A.; Østergaard, J.; Chatzivasileiadis, S. Onshore, offshore or in-turbine electrolysis? Techno-economic overview of alternative integration designs for green hydrogen production into Offshore Wind Power Hubs. *Renew. Sustain. Energy Transit.* **2021**, *1*, 100005. [CrossRef]
6. Sealhyfe. Available online: <https://www.lhyfe.com/production-unit/sealhyfe/> (accessed on 19 February 2025).
7. Hope. Available online: <https://hope-h2.eu/> (accessed on 19 February 2025).
8. Poshydor. Available online: <https://poshydor.com/en/home-en/> (accessed on 19 February 2025).
9. Serri, L.; Airolidi, D.; Lanni, F.; Naldi, R.; Castorrini, A.; Rispoli, F.; Soukissian, T.; Castro Santos, L.; Le Boulluec, M.; Maisondieu, C. Technical and economic challenges for floating offshore wind deployment in Italy and in the Mediterranean Sea. *Wiley Interdiscip. Rev. Energy Environ.* **2024**, *13*, e533. [CrossRef]
10. Vives, A.M.V.; Wang, R.; Roy, S.; Smallbone, A. Techno-economic analysis of large-scale green hydrogen production and storage. *Appl. Energy* **2023**, *346*, 121333. [CrossRef]
11. Wang, T.; Cao, X.; Jiao, L. PEM water electrolysis for hydrogen production: Fundamentals, advances, and prospects. *Carbon Neutrality* **2022**, *1*, 21. [CrossRef]
12. Ulleberg, Ø. Modeling of advanced alkaline electrolyzers: A system simulation approach. *Int. J. Hydrogen Energy* **2003**, *28*, 21–33. [CrossRef]

13. Carmo, M.; Fritz, D.L.; Mergel, J.; Stolten, D. A comprehensive review on PEM water electrolysis. *Int. J. Hydrogen Energy* **2013**, *38*, 4901–4934. [\[CrossRef\]](#)
14. Hernández-Gómez, Á.; Ramirez, V.; Guilbert, D. Investigation of PEM electrolyzer modeling: Electrical domain, efficiency, and specific energy consumption. *Int. J. Hydrogen Energy* **2020**, *45*, 14625–14639. [\[CrossRef\]](#)
15. Yodwong, B.; Guilbert, D.; Phattanasak, M.; Kaewmanee, W.; Hinaje, M.; Vitale, G. Faraday's efficiency modeling of a proton exchange membrane electrolyzer based on experimental data. *Energies* **2020**, *13*, 4792. [\[CrossRef\]](#)
16. Hancke, R.; Holm, T.; Ulleberg, Ø. The case for high-pressure PEM water electrolysis. *Energy Convers. Manag.* **2022**, *261*, 115642. [\[CrossRef\]](#)
17. Egeland-Eriksen, T.; Jensen, J.F.; Ulleberg, Ø.; Sartori, S. Simulating offshore hydrogen production via PEM electrolysis using real power production data from a 2.3 MW floating offshore wind turbine. *Int. J. Hydrogen Energy* **2023**, *48*, 28712–28732. [\[CrossRef\]](#)
18. Egeland-Eriksen, T.; Sartori, S. Techno-economic analysis of the effect of a novel price-based control system on the hydrogen production for an offshore 1.5 GW wind-hydrogen system. *Energy Rep.* **2024**, *11*, 2633–2655. [\[CrossRef\]](#)
19. Clúa, J.G.G.; Mantz, R.J.; De Battista, H. Optimal sizing of a grid-assisted wind-hydrogen system. *Energy Convers. Manag.* **2018**, *166*, 402–408. [\[CrossRef\]](#)
20. Deng, Z.; Jiang, Y. Optimal sizing of wind-hydrogen system considering hydrogen demand and trading modes. *Int. J. Hydrogen Energy* **2020**, *45*, 11527–11537. [\[CrossRef\]](#)
21. Spyroudi, A.; Wallace, D.; Smart, G.; Stefaniak, K.; Mann, S.; Kurban, Z. Offshore Wind and Hydrogen: Solving the Integration Challenge; Offshore Wind Industry Council. 2020. Available online: <https://cms.ore.catapult.org.uk/wp-content/uploads/2020/09/Solving-the-Integration-Challenge-ORE-Catapult.pdf> (accessed on 19 February 2025).
22. Tebibel, H. Methodology for multi-objective optimization of wind turbine/battery/electrolyzer system for decentralized clean hydrogen production using an adapted power management strategy for low wind speed conditions. *Energy Convers. Manag.* **2021**, *238*, 114125. [\[CrossRef\]](#)
23. Liponi, A.; Frate, G.F.; Baccioli, A.; Ferrari, L.; Desideri, U. Impact of wind speed distribution and management strategy on hydrogen production from wind energy. *Energy* **2022**, *256*, 124636. [\[CrossRef\]](#)
24. Liponi, A.; Baccioli, A.; Ferrari, L. Feasibility analysis of green hydrogen production from wind. *Int. J. Hydrogen Energy* **2023**, *48*, 37579–37593. [\[CrossRef\]](#)
25. Fei, Z.; Yang, H.; Du, L.; Guerrero, J.M.; Meng, K.; Li, Z. Two-stage coordinated operation of A green multi-energy ship microgrid with underwater radiated noise by distributed stochastic approach. *IEEE Trans. Smart Grid* **2024**, *16*, 1062–1074. [\[CrossRef\]](#)
26. Barnabei, V.F.; Ancora, T.C.M.; Conti, M.; Castorrini, A.; Delibra, G.; Corsini, A.; Rispoli, F. A Multi-Objective Optimization Framework for Offshore Wind Farm Design in Deep Water Seas. *J. Fluids Eng.* **2024**, *147*, 031105. [\[CrossRef\]](#)
27. Davis, N.N.; Badger, J.; Hahmann, A.N.; Hansen, B.O.; Mortensen, N.G.; Kelly, M.; Larsén, X.G.; Olsen, B.T.; Floors, R.; Lizcano, G.; et al. The Global Wind Atlas: A high-resolution dataset of climatologies and associated web-based application. *Bull. Am. Meteorol. Soc.* **2023**, *104*, E1507–E1525. [\[CrossRef\]](#)
28. NREL. FLORIS v3.5 Wake Modeling and Wind Farm Controls Software [SWR-17-43 and SWR-14-20]. United States 2023. Available online: <https://www.osti.gov/biblio/1993918> (accessed on 19 February 2025)
29. Bay, C.J.; Fleming, P.; Doekemeijer, B.; King, J.; Churchfield, M.; Mudafort, R. Addressing deep array effects and impacts to wake steering with the cumulative-curl wake model. *Wind. Energy Sci. Discuss.* **2022**, *8*, 401–419. [\[CrossRef\]](#)
30. Gebraad, P.M.; Teeuwisse, F.W.; Van Wingerden, J.; Fleming, P.A.; Ruben, S.D.; Marden, J.R.; Pao, L.Y. Wind plant power optimization through yaw control using a parametric model for wake effects—A CFD simulation study. *Wind Energy* **2016**, *19*, 95–114. [\[CrossRef\]](#)
31. A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Trans. Evol. Comput.* **2002**, *6*, 182–197. [\[CrossRef\]](#)
32. Blank, J.; Deb, K. pymoo: Multi-Objective Optimization in Python. *IEEE Access* **2020**, *8*, 89497–89509. [\[CrossRef\]](#)
33. Giampieri, A.; Ling-Chin, J.; Roskilly, A.P. Techno-economic assessment of offshore wind-to-hydrogen scenarios: A UK case study. *Int. J. Hydrogen Energy* **2024**, *52*, 589–617. [\[CrossRef\]](#)
34. Caputo, A. Indicatori di efficienza e decarbonizzazione del sistema energetico nazionale e del settore elettrico. *Rapp. Tecn. ISPRA* **2021**.
35. IRENA. Solutions to Decarbonise the Iron and Steel Sector. 2023. Available online: https://innovationweek.irena.org/-/media/InnovationWeek/2023-edition/Day2-Indirect-Electrification/IIW23-Day2_02-Solutions-to-decarbonise-iron-and-steel-sector.pdf (accessed on 23 January 2025).
36. Bhaskar, A.; Abhishek, R.; Assadi, M.; Somehesaraei, H.N. Decarbonizing primary steel production: Techno-economic assessment of a hydrogen based green steel production plant in Norway. *J. Clean. Prod.* **2022**, *350*, 131339. [\[CrossRef\]](#)
37. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). ERA5 Hourly Data on Single Levels from 1940 to Present; Copernicus Climate Change Service (C3S) Climate Data Store (CDS), Programme of the European Union. 2023. Available online: <https://doi.org/10.24381/cds.adbb2d47>. (accessed on 19 February 2025)
38. Emeis, S. Current issues in wind energy meteorology. *Meteorol. Appl.* **2014**, *21*, 803–819. [\[CrossRef\]](#)

39. Gaertner, E.; Rinker, J.; Sethuraman, L.; Zahle, F.; Anderson, B.; Barter, G.E.; Abbas, N.J.; Meng, F.; Bortolotti, P.; Skrzypinski, W.; et al. *IEA Wind TCP Task 37: Definition of the IEA 15-Megawatt Offshore Reference Wind Turbine*; Technical Report; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2020.
40. Hydrogen, N. MC Series PEM Electrolysers. Available online: <https://nelhydrogen.com/resources/m-series-containerized-pem-electrolysers/> (accessed on 19 February 2025).
41. Scolaro, M.; Kittner, N. Optimizing hybrid offshore wind farms for cost-competitive hydrogen production in Germany. *Int. J. Hydrogen Energy* **2022**, *47*, 6478–6493. [CrossRef]
42. Ministero dell’Ambiente e della Sicurezza Energetica. Incentivazione Degli Impianti a Fonte Rinnovabile Innovativi o Con Costi di Generazione Elevati Che Presentino Caratteristiche di Innovazione e Ridotto Impatto Sull’Ambiente e Sul Territorio. Available online: <https://www.mase.gov.it/node/18946> (accessed on 19 February 2025).
43. Tajalli-Ardekani, E.; Delibra, G.; Pizzuti, I.; Corsini, A. A Rome district transition towards optimal and sustainable heat and power generation. *Appl. Therm. Eng.* **2024**, *255*, 124001. [CrossRef]
44. Calado, G.; Castro, R. Hydrogen production from offshore wind parks: Current situation and future perspectives. *Appl. Sci.* **2021**, *11*, 5561. [CrossRef]
45. Regione Siciliana. Tabella Materiali 2024. Available online: https://www.regione.sicilia.it/sites/default/files/2024-01/Tabella%20materiali%202024_0.pdf (accessed on 19 February 2025).

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.