Energy Reports 14 (2025) 3093–3104

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Exploring the economic feasibility of offshore wind energy for sustainable development

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ARTICLE INFO

Keywords:
Economic analysis
Italy
Offshore wind
Renewable resource
Sustainable development

ABSTRACT

Offshore wind farms play a crucial role in the transition to low-carbon energy systems, offering a scalable and renewable solution to meet growing energy demands. Technological advancements and innovation are key enablers in enhancing the performance, reliability, and cost-efficiency of such infrastructure. However, environmental protection objectives do not always align seamlessly with the deployment of offshore wind projects, underscoring the importance of robust economic evaluations to guide policy and investment decisions. This study investigates the economic feasibility of an offshore wind farm planned off the coast of central Italy, employing a comprehensive set of financial indicators. The findings indicate that the project is economically viable: the Net Present Value (NPV) ranges from 195 to 1324 €/kW, the Internal Rate of Return (IRR) lies between 9 % and 15 %, the Profitability Index (PI) spans 0.50–1.02, the Discounted Payback Time (DPBT) varies from 11 to 20 years, and the Levelized Cost of Electricity (LCOE) is between 125 and 138 €/MWh. Key variables such as the energy selling price, energy inflation rate, and capacity factor significantly affect the economic performance. Risk analysis shows that under favourable market conditions, the economic risk is low, while it becomes moderate in less favourable scenarios. By integrating technological and innovative dimensions into the economic assessment and exploring multiple market scenarios, this study offers a robust foundation for evidence-based decision-making. The development of offshore wind projects not only supports the achievement of Sustainable Development Goal 7 but also strengthens national energy independence and resilience.

1. Introduction

The transition towards a low-carbon energy future has positioned renewable energy sources at the lead of global energy policy and investment. Among these, offshore wind power stands out due to its vast resource potential, higher capacity factors compared to onshore wind, and ability to be deployed at scale, offering a significant contribution to reaching climate mitigation goals (Bilgili et al., 2011). As countries attempt to increase energy security and meet commitments under international agreements like the Paris Agreement, offshore wind is increasingly recognized as a key technology for decarbonizing electricity generation (Martinez et al., 2023; Sharma et al., 2022). Such a transition, which is increasingly driven by renewable energy technologies like offshore wind farms, plays a crucial role in advancing several of the United Nations' Sustainable Development Goals (SDGs). Specifically, the offshore wind projects contribute significantly to goals such as affordable and clean energy (SDG 7), sustainable cities and communities (SDG 11), climate action (SDG 13), and life below water (SDG 14). Therefore, these types of renewable projects are a key factor for sustainable transition within the SDGs framework (Si et al., 2024; Peraki et al., 2025).

The development of offshore wind projects, however, represents a complex activity involving significant interactions with marine

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https://doi.org/10.1016/j.egyr.2025.10.003
Received 2 July 2025; Received in revised form 29 August 2025; Accepted 8 October 2025
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Nomenclature

BEP	Break-Even Point
CO2	Carbon dioxide
DCF	Discounted Cash Flow
DPBP	Discounted Payback Period
DPBT	Discounted Payback Time
HM	High Market
HMC	High Market with alternative Capacity factor
HMI	High Market with alternative Inflation rate
HMIC	High Market with alternative Inflation rate and alternative Capacity factor
HMW	High Market with alternative WACC
HVAC	High-Voltage Alternating Current
HVDC	High-Voltage Direct Current
IRR	Internal Rate of Return
LCOE	Levelized Cost of Electricity
LM	Low Market
LMC	Low Market with alternative Capacity factor
LMI	Low Market with alternative Inflation rate
LMIC	Low Market with alternative Inflation rate and alternative Capacity factor
LMW	Low Market with alternative WACC
MASE	Ministry of the Environment and Energy Security
MW	Mega Watt
NPV	Net Present Value
O&M	Operation & Maintenance
PI	Profitability Index
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SDGs	Sustainable Development Goals
SLR	Systematic Literature Review
WACC	Weighted Average Cost of Capital

ecosystems, coastal communities, and existing maritime activities (Fowler et al., 2018). Achieving sustainability in this renewable context is inherently multi-dimensional, requiring a balanced integration of environmental, social, and economic pillars with a pragmatic approach (Basilico et al., 2025). A complete valuation of offshore development must therefore consider not only the environmental impacts and benefits (Fowler et al., 2018; Snyder and Kaiser, 2009) but also the social dimensions, including public acceptance, community benefits, and effects on industries like fishing and tourism (Betakova et al., 2015; Ladenburg, 2009). Key environmental considerations include minimizing impacts on marine and avian life (Desholm and Kahlert, 2005; Drewitt and Langston, 2006), managing noise (Benhemma-Le Gall et al., 2011), and understanding habitat changes (Inger et al., 2009; Dierschke et al., 2016). Social aspects involve navigating potential conflicts with traditional activities like fishing and tourism (Voltaire et al., 2017), ensuring community engagement and acceptance (Bergquist et al., 2020; Batel, 2018; Kermagoret et al., 2016) and addressing visual impacts (Betakova et al., 2015; Ladenburg, 2009; Sullivan et al., 2000; Devine-Wright and Wiersma, 2020). Another key factor that influences the adoption of this technology is its economic sustainability (i.e., its ability to generate sufficient revenue and value over its lifecycle to cover costs and remain financially viable). Given the large capital investment required, covering manufacturing costs, complex marine installation, long-term operation in harsh conditions, and eventual decommissioning, a detailed analysis of the economic viability is essential for policymakers, investors, and project developers (Virtanen et al., 2022; Pires et al., 2022a). The growth of wind power covers large areas globally due to its vast potential (von Krauland et al., 2023; Jafar-Nowdeh et al., 2020).

Offshore wind shows strong potential for green hydrogen production, though economic factors remain critical. Technological advancements and learning rates in emerging systems like floating wind turbines and electrolysers can significantly reduce production costs (Balcı and Erbay, 2025; Pegler et al., 2025). Building upon this growing importance, a comprehensive understanding of the economic sustainability of offshore wind projects is crucial for successful deployment. Although extensive research has examined the economic dimensions of single cases - often revealing a downward trend in costs (Vieira et al., 2019) - a comprehensive overview of the broader economic factors, including both costs and benefits, based on a systematic review of the literature, is still missing.

To address this critical gap, a dedicated Systematic Literature Review (SLR) on the economic sustainability of offshore wind energy has been conducted. The decision-making process inherently involves a wide range of factors (Martinez and Iglesias, 2024; Jung et al., 2024), including the essential need for economic assessments that account for the potential of currently underexplored regions (Gao et al., 2024). As a result, investment decisions in offshore wind farms require the development of analytical models capable of integrating diverse economic and technical parameters (Malleret et al., 2024).

This study aims to evaluate the economic viability of an offshore wind project through the analysis of both baseline and alternative scenarios. To this end, a range of key financial indicators are employed, including Net Present Value (NPV), Internal Rate of Return (IRR), Discounted Payback Time (DPBT), Profitability Index (PI), and Levelized Cost of Electricity (LCOE). These indicators are analyzed across varying critical parameters, such as investment and operation & maintenance (O&M) costs, energy selling price, energy yield, inflation rate, weighted average cost of capital (WACC), and capacity factor. By grounding the case study in the comprehensive evidence derived from the SLR, this study delivers a rigorous and evidence-based assessment of the economic viability of offshore wind farm development within a specific regional context, thereby offering valuable insights for investors and policy formulation.

The remainder of this paper is structured as follows: Section 2 details the results from the Systematic Literature Review on the economic sustainability evidence of offshore wind farms. Section 3 presents the methodology and data used, Section 4 presents the results, Section 5 compares the findings with the evidence from the literature, and Section 6 concludes the paper.

2. Literature review

The topic of renewable energy is vast and multifaceted, driven by the need to reduce energy consumption and support the development of certification systems (Vassiliades et al., 2025). Some studies concentrate on the residential sector (Zubair and Abbas, 2025), while others examine commercial (Antonini et al., 2025) and industrial (Hosseini Dehshiri and Firoozabadi, 2024) applications. Increasing attention is also being given to renewable energy communities (Basilico et al., 2025), energy communities and island systems (Barone et al., 2021), where the interplay between renewable energy and water resources is becoming a key area of interest (Buonomano et al., 2022). Within this broader context, offshore wind energy has emerged as a significant focus of technical research (Li et al., 2025; Si et al., 2025).

The economic sustainability of offshore wind farms is a critical area of study given their central role in the global energy transition. While numerous reviews have addressed technical aspects of wind farms (e.g Díaz and Guedes Soares, 2020; Joselin Herbert et al., 2014), a comprehensive Systematic Literature Review specifically focused on the economic sustainability of offshore wind farms. The usefulness of this

analysis had been proposed in previous studies showing the strategic role of offshore wind farms (Pires et al., 2022b). To fill this gap, we conducted an SLR adhering to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Page et al., 2021); guidelines and following the procedure described by (Avenali et al., 2023). This structured approach minimizes bias and provides a robust foundation for the economic evidence on offshore wind farms.

The database used for the literature search was Scopus (www.scopus.com). A search strategy was formulated based on the study's objectives, was applied to the TITLE-ABS-KEY Scopus's fields to ensure relevance. The search query employed was: *"offshore" AND "economic analysis" AND "cost" AND "wind power" AND NOT ("hydrogen" OR "photovoltaic" OR "gas")*. The query was executed in date December 2024. This strategy was guided by the Population, Interest, Context and Outcome (PICO) model (Brandt Eriksen et al., 2018) and aimed to exclude concepts (e.g., hydrogen, photovoltaic, gas) that, while related to the offshore domain, did not support the specific focus of this study.

An initial group of 84 potentially articles was identified. Following the PRISMA guidelines, inclusion and exclusion criteria were applied. As inclusion criteria the publication language (English only), a defined time period (2015–2025) to ensure relevance considering the rapid technological change of wind farm technologies, and limitation to specific subject areas ("Energy", "Economic analysis") to maintain focus. During the screening process, articles were excluded based on predefined criteria:

1. Focus not on economic analysis (12 articles excluded).
2. Insufficient data presented (7 articles excluded).
3. Topic not aligned with the research scope (11 articles excluded).
4. Study outdated, not reflecting current technologies or market conditions (6 articles excluded).

After applying these criteria, a final set of 24 articles was considered suitable and included in the final literature analysed. The PRISMA flow diagram summarizing this process is presented in Fig. 1. Drawing upon this collection of studies, the rest of this section presents the key findings concerning the economic sustainability of offshore wind farms.

The economic analysis for constructing an offshore wind farm necessitates a structured approach, typically segmenting costs into several primary categories to evaluate overall economic feasibility and sustainability over the project lifecycle. The cost structure for establishing an offshore wind farm is multi-faceted, beginning with substantial project development costs. These include comprehensive feasibility studies covering site assessment, wind resource analysis, environmental impact studies, and the complex process of securing regulatory approvals (Filgueira-Vizoso et al., 2022, 2023; Castro-Santos et al., 2023). A critical element from the outset is the chosen economic assessment methodology, with a lifecycle cost approach being widely adopted to

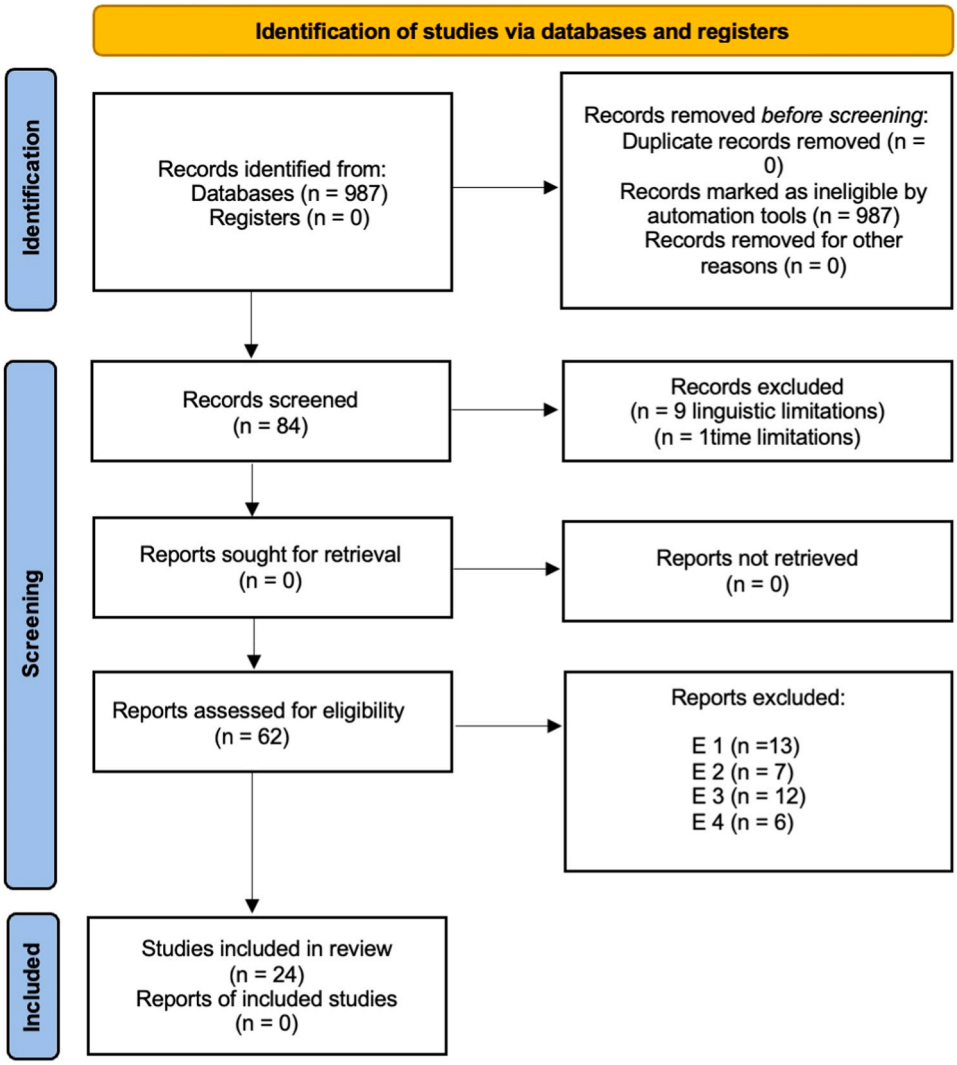

Fig. 1. PRISMA flow diagram.

capture expenses across conception, design, production, installation, operation, and decommissioning phases (Castro-Santos et al., 2016). Obtaining the necessary permits and licenses is also a key initial expense (both in terms of money and time).

Following development, significant construction costs are encountered. Wind turbines represent the largest component, involving manufacturing, transport, and installation. While larger turbines demand higher initial investment, their potential for greater energy yield impacts the cost-benefit calculation (Lin et al., 2020). Foundations, adapted to specific seabed conditions and water depths (e.g., monopiles, jackets, floating), and the extensive network of subsea cables connecting turbines to offshore substations and the grid are also major cost drivers (Roy et al., 2023; Shi et al., 2024). The offshore substation itself is a crucial, costly piece of infrastructure. Transportation and logistics costs, involving specialized vessels for moving large components, add further to the construction expenditure.

During the operational life, O&M costs emerge as one of the most significant expenditures, potentially reaching 25 % of the total lifecycle costs estimated during the design phase (Roy et al., 2023; Tusar and Sarker, 2022). Finally, decommissioning costs at the end of the typical 20–25 years lifespan involves the expense of removing the infrastructure (Speranza et al., 2021). Other indirect costs, such as financing expenses, are heavily influenced by external factors like government subsidies, taxation, and investor expectations (Nguyen and Chou, 2018; Zountouridou et al., 2015), while contingencies for unforeseen technical or financial risks, although difficult to quantify, are part of the project consideration.

Economic sustainability is fundamentally determined by balancing these costs against the benefits and value generated over the project's lifespan. The primary benefit of an offshore wind farm is the generation of clean electricity, providing revenue through energy sales over the project's operational life (typically 20–25 years) (Lee et al., 2019). Financial incentives from governments, including feed-in tariffs or tax credits, are consistently identified as significantly enhancing feasibility by improving the cost-benefit ratio (Nguyen and Chou, 2018; Zountouridou et al., 2015). Furthermore, offshore wind avoids the costs associated with purchasing fossil fuels and carries the critical benefit of reduced Carbon dioxide (CO_2) emissions. These avoided emissions can possess economic value through carbon pricing mechanisms or the prevention of climate change impacts. The development and operation of wind farms also stimulate broader economic growth by creating jobs across the construction, manufacturing, installation, operation, and maintenance phases.

Key economic methods frequently employed to assess financial viability and balance investment against revenue and avoided costs include IRR, NPV, DPBP (Castro-Santos et al., 2018), and LCOE. The LCOE, representing the average cost of producing electricity over the plant's life (around 40–70 €/MWh for modern offshore farms), serves as a key indicator of the project's economic competitiveness and sustainability (Filgueira-Vizoso et al., 2022; Castro-Santos et al., 2016).

Numerous factors are shown to drive variations in the cost-benefit profile and, consequently, the economic sustainability of offshore wind projects. Site-specific conditions, including wind resource availability, water depth, and seabed characteristics, directly impact both construction costs (related to foundations and installation complexity) and the potential for energy generation (the primary benefit) (Schweizer et al., 2016). Technological choices, such as turbine size, foundation type, grid connection architecture (e.g., High-Voltage Alternating Current, HVAC vs. High-Voltage Direct Current, HVDC), and the integration of energy storage systems, represent critical trade-offs between upfront capital expenditure and long-term operational efficiency and energy yield (Gao et al., 2024; Roy et al., 2023; Shi et al., 2024; Speranza et al., 2021; Katsaprakakis, 2016). The unpredictable nature of O&M costs, influenced by component reliability (e.g., gearboxes are noted for high failure rates) (Roggenburg et al., 2020) and harsh offshore environmental conditions, is a significant variable affecting long-term profitability. Furthermore, the regulatory and political landscape, considering the permitting processes, the availability of subsidies, and the taxation policies, plays a critical role in shaping project economics, as do prevailing electricity market prices and demand dynamics (Nguyen and Chou, 2018; Zountouridou et al., 2015). Geographical location introduces variability in labor costs, weather conditions, and specific legal and political factors, leading to considerable differences in project costs across countries and even regions (Gao et al., 2024; Aguirre-Suso et al., 2014; Riaz and Khan, 2019; Gao et al., 2014; Sim, 2023; Cali et al., 2018; Gao et al., 2023).

Beyond the direct economic analysis, the literature confirms that offshore wind projects contribute significantly to several of the United Nations SDGs. Most directly, the offshore wind farms contribute to the SDG 7 by providing a renewable source of electricity and increasing the share of clean energy in the global mix. By generating electricity without significant greenhouse gas emissions, offshore wind projects are a powerful tool for fighting climate change, directly contributing also to the SDG 13 and providing the significant benefit of CO_2 emission reductions (Zountouridou et al., 2015).

For an offshore wind project to effectively contribute to broader SDGs, its economic sustainability is paramount. This sustainability hinges on the careful management of costs and the maximization of benefits throughout the project's lifecycle. A financially viable project ensures continued operation, sustained clean energy production, ongoing employment, and long-term contributions to decarbonization targets. Scholarly literature underscores that economic viability transcends a mere financial objective; it serves as a fundamental prerequisite for realizing the full sustainable development potential of offshore wind farms.

Key determinants of an offshore wind farm project's economic sustainability encompass substantial initial development and construction costs - notably for turbines, foundations, subsea cables, and the offshore substation - alongside significant long-term O&M expenditures. These financial outlays are offset by the primary revenue stream from electricity sales and any governmental financial incentives. The overall economic feasibility is also significantly influenced by site-specific conditions, technological choices, the regulatory environment, market prices, and geographical location. Moreover, while challenging to quantify precisely, other beneficial factors such as the economic value of avoided CO_2 emissions and the impetus to broader economic growth through job creation merit consideration within a comprehensive sustainability assessment.

In conclusion, the evaluation of an offshore wind farm project's economic sustainability typically involves methodologies such as NPV and LCOE. Given the literature's emphasis on the significant impact of various external factors on the costs and benefits outlined, conducting a sensitivity analysis is an essential step in accurately estimating the economic sustainability of a new offshore farm.

3. Data and methods

This section presents the methodological structure of this work, which first involves a technical analysis (Section 3.1) and then a description of the economic model (Section 3.2).

3.1. Technical analysis

The Italian territory includes several areas with some of the highest percentages of strong and consistent winds recorded throughout the year - ideal conditions for offshore installations. Notable regions include southern Sicilia, Sardegna, Liguria, and eastern Puglia (Sperati et al., 2024). While existing literature primarily focuses on Puglia (Caporale et al., 2024) and Sicilia (Serri et al., 2020), it is equally important to consider a diversified mix of regions, such as combining Sicilia with Emilia-Romagna (Lanni et al., 2025). That said, the broader challenges of sustainability call for contributions from all territories, making it

essential to also evaluate areas like Toscana (Ronchetti et al., 2025).

Site selection was guided by key primary factors: wind potential, seabed depth and conditions, proximity to and connectivity with the electrical grid, and the availability of port infrastructure. Secondary considerations included the site's distance from relevant islands, potential social impacts - particularly those related to tourism - and the presence of major maritime routes.

Two additional criteria played a decisive role in the final site selection: avoiding environmentally protected areas, such as the Parco Regionale della Maremma, and ensuring proximity to the town and port of Piombino. The selected site lies approximately 10 kilometres off the coast of Castiglione della Pescaia (Figure S1).

Preliminary analyses indicate that the area identified for the offshore wind farm installation does not present any significant environmental, archaeological, or navigational constraints. Specifically, the site is not located within any marine protected areas, is free from archaeological restrictions, and is not intersected by major shipping routes.

The project entails the installation of ten floating wind turbines, for a total nominal capacity of 55 MW. Each turbine has a nominal output of approximately 5.5 MW, with units spaced about 250 m apart and reaching a height of around 100 m above sea level. The rotor diameter measures approximately 155 m, and the hub height is about 103 m. Table S1 provides further technical data (Wind-turbine-model, 2025).

Several technical analyses have identified the following parameters: the expected operational lifespan of offshore wind farms is typically around 30 years (Brussa et al., 2023), although some estimates suggest a more conservative range of 20–25 years (Li et al., 2022). The capacity factor - defined as the ratio between the actual energy produced and the energy that would be generated if the plant operated at full capacity year-round - ranges in Italy from 25 % to 45 % (Serri et al., 2020). For this reason, an intermediate value of 35 % is often used in performance evaluations (Bonesso et al., 2025).

To estimate the plant's net annual energy output, i.e. the amount of energy effectively available for sale, several steps were followed. Monthly wind data was identified based on sites such as weatherspark.com and meteoblue.com (Figure S2). In addition, other data was initially extracted from AEOLIAN, the Italian wind atlas developed by RSE, and then cross-checked against findings from existing literature (Pires et al., 2022b; Lanni et al., 2025; Bonesso et al., 2025; Tumminelli et al., 2023).

From this, losses and the annual degradation of performance over the plant's lifespan were factored in to determine a realistic net production estimate. The assessments were verified by cross-checking data from literature and reports and were validated by two experts in the field to ensure the highest level of accuracy in the estimates – Table 1.

3.2. Economic model

The model analysis is based on the Discounted Cash Flow (DCF) method, a fundamental economic tool for this type of evaluation. DCF is particularly valuable because it accounts for the time value of money by discounting projected cash flows to their present value and is widely used to evaluate wind farm projects (Malleret et al., 2024; Yeter et al., 2023). The analysis is based on the following key financial indicators: (i) NPV, which quantifies the total wealth generated by the project; (ii) PI, which indicates the return per € invested; (iii) DPBT, which measures the time required to recover the initial investment; and (iv) IRR, which represents the project's expected annual percentage return (D'Adamo et al., 2025).

Table 1
Technical input data (Pires et al., 2022b; Lanni et al., 2025; Li et al., 2022; Bonesso et al., 2025; Tumminelli et al., 2023).

Technical data	
Variable	**Value**
Lifetime of the plant	25 years
Capacity factor	35 %
Gross annual production	168,630 MWh/y
Estimated losses	8 %
Net annual production	155,139.6 MWh/y
Annual decline of the plant	0.5 %

As highlighted in Section 2, another important parameter is the LCOE, which allows the average cost of energy produced from different sources over the useful life of a plant to be compared. This parameter varies greatly in Europe depending on the country in which the system is installed, ranging from 95 to 160 €/MWh (Martinez and Iglesias, 2022). The LCOE is defined as the ratio between the total costs of an energy project and the total electricity it produces over its operational lifetime. Following the approach proposed by some authors (Martinez and Iglesias, 2022), this is obtained by dividing all costs (investment and operating) by the total energy produced, both discounted.

A key parameter in DCF is the WACC, estimated at 7.5 %. The literature suggests other values in terms of discount rates, such as 5 % (Maienza et al., 2022), 6 % (Bonesso et al., 2025), 7 % (Aldersey-Williams et al., 2019) and 8 % (Schweizer et al., 2016).

The project costs can be grouped into four main categories. Initial investment costs relate to the purchase of the ten wind turbines and the structural works required to ensure the plant's success. The wind turbines represent the main component of the cost, including production, transport and installation (Lin et al., 2020). Another key component is cables and connections, which include submarine cables for connecting the turbines to the offshore substation and the onshore electricity grid, known as land-sea connections, and substations (Roy et al., 2023; Shi et al., 2024). For all cost items, reports from the International Energy Agency, the European Wind Energy Association and the Ministry of the Environment and Energy Security (MASE) are also consulted.

Operative costs refer to the annual expenses required throughout the entire operational life of the plant. While many of these costs relate directly to the operation and maintenance of the turbines (5 % on the investment cost), they also include insurance premiums (0.3 % on the investment cost) and fees payable to local authorities (0.1 % on the investment cost) that have granted permission for the plant's installation in the selected area. These estimates are likewise supported by data and benchmarks found in literature (Tusar and Sarker, 2022; Garcia-Teruel et al., 2022; Pantusa et al., 2020).

The investment capital has been structured into two components: a 30 % equity share, amounting to 21,480,000 €, and a 70 % debt share, totalling 50,120,000 €. The debt will be repaid over a ten-year period at a fixed interest rate of 2 %. This results in an annual repayment of 5012,000 €. Not accounting for the time value of money, the total interest paid over the loan term exceeds 1 million €.

The final item to be considered is the decommissioning cost - the expense associated with dismantling the plant at the end of its operational life (Speranza et al., 2021). Several studies highlight the strategic importance of including this cost in investment evaluations. For this analysis, a decommissioning cost equal to 0.2 % of the initial investment has been assumed, amounting to 143,200 €, to be incurred at the end of the plant's life cycle. For economic data, a comparison was also made with the experts consulted for technical data – Table 2.

Regarding revenues, four scenarios were analysed to account for varying market conditions and reflect the dynamic nature of the energy sector. Specifically, two scenarios are based on different market price assumptions, while the other two consider different fixed-price contract settings. The scenarios evaluated are as follows:

- LM - Low Market scenario in which the energy selling price is set at 130 €/MWh.
- LMI - Low Market scenario in which the energy selling price is set at 130 €/MWh with annual energy price inflation of 2 %.
- HM - High Market scenario in which the energy selling price is set at 160 €/MWh.
- HMI - High Market scenario in which the energy selling price is set at 160 €/MWh with annual energy price inflation of 2 %.

Table 2
Economic input data (Lin et al., 2020; Roy et al., 2023; Shi et al., 2024; Tusar and Sarker, 2022; Speranza et al., 2021; Garcia-Teruel et al., 2022; Pantusa et al., 2020; Rinaldi et al., 2021).

Investment cost	
Variable	**Value**
Wind turbines	57,000,000 €
Grid connection	4400,000 €
Electrical infrastructure	2000,000 €
Transport and installation	2700,000 €
Civil works	4000,000 €
Land-sea junction	1000,000 €
Underground export cable duct	1500,000 €
Electrical transformation and delivery substation	1500,000 €
Other costs	1500,000 €
Control systems	200,000 €
Consultancy	300,000 €
Financial costs	1000,000 €
Initial investment	71,600,000 €
Operative cost	
Variable	**Value**
Operations and maintenance	3580,000 €/year
Charges payable to local authorities	71,600 €/year
Insurance	214,800 €/year

To ensure a robust analysis, the first step was to identify the critical variables - those with the greatest influence on the project's outcomes when subject to variation within defined ranges. Once these variables were determined, the following types of analysis were conducted:

- Sensitivity Analysis, which examines the impact of varying one critical variable at a time on the project's value.
- Scenario Analysis, which differs from sensitivity analysis by evaluating the effects of simultaneous changes in multiple variables.
- Risk Analysis, which involves the simultaneous variation of several variables by assigning each a probability distribution defined by a mean and a standard deviation. For this purpose, the Monte Carlo method was employed to simulate 1000 iterations of the NPV.

4. Results

This section presents and discusses the results of the financial analysis conducted on the case study. By thoroughly evaluating the data, the economic performance of the plant over its estimated 25-year life cycle is examined. The primary objective is to determine whether the project can generate value while maintaining long-term sustainability and profitability assessing baseline (Section 4.1) and alternative (Section 4.2) scenarios.

4.1. Baseline scenario

The first analysis conducted for this case study focuses on the base scenario. Estimating the profitability of a wind farm over its entire life cycle is inherently complex due to the uncertainty of future cash flows and the potential for technological advancements over such a long-time horizon. The analysis is carried out across the four contexts outlined in Section 3.2. Figures S3-S7 present the discounted cash flows for all scenarios analysed, while Table 3 shows the financial indicators.

The results confirm the economic viability of the project across all scenarios. However, there are significant differences in NPV outcomes. Regardless of the assumed energy inflation rate of 2 %, the High Market (HM) scenarios yield substantially higher profits, with NPVs ranging from 41.8 million € to 72.8 million €. In contrast, the Low Market (LM) scenarios show lower profitability, with NPVs ranging from 10.7 million € to 35.9 million €.

Table 3
Profitability analysis.

	NPV	NPV/Size	IRR	PI	DPBT
Scenario LM	10,724,596 €	195 €/kW	9 %	0.15	19 y 11 m
Scenario HM	41,825,275 €	760 €/kW	13 %	0.58	12 y 7 m
Scenario LMI	35,911,866 €	653 €/kW	12 %	0.50	15 y 3 m
Scenario HMI	72,824,991 €	1324 €/kW	15 %	1.02	11 y 1 m

In terms of specific NPV values per installed power, the HM scenario outperforms LM by 565 €/kW, while the HM with Inflation (HMI) scenario exceeds LM with Inflation (LMI) by 671 €/kW. The impact of energy price inflation is also notable: HMI results in a 564 €/kW increase compared to HM, and LMI shows a 458 €/kW increase over LM. In conclusion, favorable market conditions - particularly those reflecting a sales price of 30 €/MWh - have a substantial impact on project value. Moreover, the inclusion of inflation significantly enhances long-term profitability, highlighting the importance of accounting for future price increases in financial forecasts.

As highlighted, NPV was also proposed based on the size of the plant, as this facilitates comparison between case studies. It is therefore useful to evaluate the PI that performs the same function, but this time comparing the expected profit with the expected investment. Given that no budget limit is considered, the PI can be compared in their entirety, and it emerges that in the most favourable scenario (HMI), a value of 1.02 is achieved, while the least favourable scenario has a low value of 0.15 € for every € invested.

As regards the IRR, there are no traps and it can therefore be calculated. The results are consistent with those of the NPV, as the value is always higher than the WACC. It emerges that in the high market scenarios there is a percentage higher than 3–4 % compared to the low market scenarios. The extreme cases see 9 % associated with the LM scenario and 15 % with the HMI scenario. Furthermore, the DPBT is quantified, which in turn reaches a value of 19 years and 11 months in the LM context and 11 years and 1 month in the HMI context. The cutoff period is not provided, so we cannot say whether the project is accepted or not. The value obtained is certainly lower than the worst cutoff period, which is equal to the lifetime of the project. In high market scenarios, the value is less than half the useful life of the project.

Before proceeding with the analysis of alternative scenarios, attention was directed toward the LCOE. This metric represents the minimum price at which electricity must be sold to cover all costs associated with the plant over its lifetime. The results show that the base value of LCOE is 138 €/MWh. However, to give the results greater solidity, the values of 4 %, 5 %, 7 % and 9 % proposed in other studies are also taken into consideration. The analysis revealed that LCOE is highly sensitive to the WACC: it stands at 74 €/MWh with a WACC of 4 % and rises sharply to 184 €/MWh with a WACC of 9 %. At the same time the following values are obtained: 88 €/MWh, 125 €/MWh and 138 €/MWh with a WACC of 5 %, 7 % and 7.5 % respectively (Figure S8). These figures clearly highlight how strongly LCOE is influenced by this parameter. To support these findings, a comparison with values reported in existing literature is also proposed (Table 4 - Figures S9-S10).

Table 4
Literature analysis - LCOE.

Location	Value	Reference
Gulf of Lion (France)	95 €/MWh	(Martinez and Iglesias, 2021)
Sardegna, Sicilia (Italy)	130–180 €/MWh	(Martinez and Iglesias, 2021)
Balearic Islands (Spain)	200–250 €/MWh	(Martinez and Iglesias, 2021)
Sicilia (Italy)	100–125 €/MWh	(Ghigo et al., 2020)
Puglia (Italy)	269–334 €/MWh	(Pantusa et al., 2020)
Italy	70–156 €/MWh	(Serri et al., 2020)
Sardegna (Italy)	95–121 €/MWh	(Travaglini et al., 2023)
Greece	88 €/MWh	(Konstantinidis et al., 2014)
Turkey	82–136 €/MWh	(Cali et al., 2018)
Italy	91–106 €/MWh	(Maienza et al., 2020)
Aegean Sea (Turkey)	91 €/MWh	(Satir et al., 2018)
Sicilia (Italy)	122–137 €/MWh	(Cottura et al., 2021)

4.2. Alternative scenarios

As already stated, an investment project brings with it the problem of unpredictability due to the length of the plant's useful life. The first analysis carried out is that of sensitivity. In particular, the following critical variables were selected for subsequent analysis: i) WACC; ii) initial investment cost; iii) maintenance costs; iv) energy price; v) net energy productivity; and vi) capacity factor. The analyses are conducted both in a pessimistic context, where two case studies are considered for each critical variable, and in an optimistic context, where a single case study is analysed. The variation deltas are shown in Tables S2-S3. The analyses are conducted solely for the two base scenarios HM and LM.

This study examines a range of pessimistic and a few optimistic scenarios to quantify the impact of key variables on the project's expected economic return. The goal is to identify the main risk factors and develop effective mitigation strategies. This analysis helps highlight which elements require closer attention during project planning and management, thereby enhancing resilience to external shocks and market uncertainties. Table 5 presents the NPV results for the pessimistic scenario.

The sensitivity analysis of the project's NPV highlights the influence of various economic and operational factors under two contrasting market scenarios: a favourable HM scenario and an unfavourable LM scenario. The results indicate that while the project is generally resilient under average conditions, it becomes vulnerable under extreme scenarios, warranting careful strategic planning. In the HM scenario, only 1 out of 12 case studies results in a negative NPV - specifically, the case with a 10 % reduction in the capacity factor. Conversely, in the LM scenario, 7 out of 12 cases yield negative NPVs. This underscores that in low-price environments, the project is particularly sensitive to negative shifts in key parameters such as the WACC and capacity factor. The analysis further reveals that the project retains its economic viability primarily when changes in critical variables remain within certain thresholds or when high electricity prices, as seen in the HM scenario, are assumed. Notably, with the exception of increases in O&M costs, all other pessimistic variable shifts lead to negative NPVs in the LM scenario - highlighting the need for focused risk mitigation in less favourable market conditions. In addition to evaluating critical scenarios, it is equally important to assess favourable conditions that could enhance the project's profitability (Table 5). Under these optimistic assumptions, the analysis clearly shows that the project has strong potential for success and can generate substantial long-term returns.

In conclusion, the sensitivity analysis confirms that the most influential factors affecting the project's economic performance are the WACC and the capacity factor. However, the comparison between the HM and LM scenarios highlights the critical importance of energy sales prices, which ultimately play a fundamental role in determining the project's financial viability.

The next alternative analysis carried out is a scenario analysis, in which several variables are varied simultaneously (Table S4). Negative case studies are considered in which the main cost items, i.e. investment and O&M costs, are varied simultaneously by two different percentages (10 % and 20 %). On the revenue side, a hybrid case study is evaluated in which two different reductions in the energy sales price (-10 €/MWh and −20 €/MWh) are assumed and two different inflation rates are analysed (1.5 % and, considering the alternative context, from 2 % to 3.5 %). Finally, a new pessimistic scenario was analysed in which, in addition to the two above-mentioned costs being reduced by 10 %, a reduction in the capacity factor was considered for two different percentages (5 % and 10 %). Table 6 shows the NPV obtained in the various case studies.

The analysis of the project reveals an economic structure with solid foundations of profitability, while also highlighting areas of vulnerability that require careful oversight. The multidimensional assessment - encompassing both optimistic and pessimistic scenarios - offers a thorough mapping of the project's financial resilience. The findings of this scenario analysis reinforce the results of the earlier analysis: under the HM scenario, only one out of eight case studies showed a negative NPV, whereas under the LM scenario, three out of eight did. A simultaneous variation in costs negatively impacts profitability, but only when the reduction reaches 20 %; in such a case, the investment is not viable under the LM scenario.

Regarding the combined effect of energy sales price and inflation, it is notable that a price reduction of 10 €/MWh coupled with 1.5 % inflation actually enhances profitability - an outcome not observed when the price drop reaches 20 €/MWh. Conversely, with inflation at 3.5 %, the resulting revenue increase consistently offsets the reduction in energy prices, underscoring the significant role that long-term price escalation, driven by inflation, plays in shaping economic outcomes (D'Adamo et al., 2025). The pessimistic scenario - characterized by both reduced costs and lower energy output - leads to unprofitability across multiple cases. This underscores the central importance of operational efficiency to the project's economic sustainability. Likewise, the variability observed across different inflation rates and between HM and LM scenarios highlights the project's sensitivity to macroeconomic and operational conditions.

The next step is to apply the Monte Carlo method to provide numerical simulations repeated several times, offering a complete perspective on the risk of the project in question. The analyses cover the

Table 5
Sensitivity analysis (NPV).

	Pessimistic context	
	Low market	**High market**
1.5 % increase in WACC	−504,323 €	26,982,663 €
3 % increase in WACC	−9617,101 €	14,904,715 €
10 % increase in investment costs	3564,596 €	34,665,275 €
20 % increase in investment costs	−3595,404 €	27,505,275 €
10 % increase in annual O&M costs	7392,928 €	38,493,607 €
20 % increase in annual O&M costs	3864,357 €	35,999,478 €
5 % decrease in net producibility	3986,116 €	33,531,761 €
10 % decrease in net producibility	−2752,364 €	25,238,246 €
10 €/MWh decrease in energy price	357,703 €	31,458,382 €
20 €/MWh decrease in energy price	−10,009,189 €	21,091,489 €
5 % decrease in capacity factor	−8528,205 €	18,129,520 €
10 % decrease in capacity factor	−27,781,006 €	−5566,235 €
	Optimistic context	
	Low market	**High market**
1.5 % reduction in WACC	24,705,634 €	60,258,434 €
10 % reduction in investment costs	17,884,596 €	48,985,275 €
10 % reduction in annual O&M costs	12,381,187 €	43,481,865 €
10 % increase in net productivity	17,463,077 €	50,118,789 €
10 €/MWh increase in energy price	21,091,489 €	52,192,168 €
5 % increase in capacity factor	29,977,398 €	65,521,030 €

Table 6
Scenario analysis (NPV).

	Low market	**High market**
10 % increase in investment costs + 10 % increase in annual O&M costs	4528,532 €	35,629,211 €
20 % increase in investment costs + 20 % increase in annual O&M costs	−5125,597 €	25,975,082 €
10 €/MWh decrease in energy price + 1.5 % inflation	17,225,249 €	52,542,814 €
20 €/MWh decrease in energy price + 1.5 % inflation	5452,727 €	40,770,292 €
10 €/MWh decrease in energy price + 3.5 % inflation	45,463,152 €	87,840,193 €
20 €/MWh decrease in energy price + 3.5 % inflation	31,337,472 €	73,714,512 €
10 % increase in investment costs + 10 % increase in annual O&M costs + 5 % decrease in capacity factor	−14,724,269 €	11,933,456 €
10 % increase in investment costs + 10 % increase in annual O&M costs + 10 % decrease in capacity factor	−33,977,070 €	−11,762,299 €

three critical variables (energy price, investment cost, O&M cost) and Table S5 provides their average value and standard deviation for the different contexts. In fact, it is decided to consider not only the LM, HM, LMI and HMI scenarios, but also scenarios that assess the role of the capacity factor, in which a 5 % reduction in this value was considered. This choice is justified by the results obtained in sensitivity and scenario analyses, which show the key role of this parameter. Therefore, the Low Market with alternative Capacity factor (LMC), High Market with alternative Capacity factor (HMC), Low Market with alternative Inflation rate and alternative Capacity factor (LMIC) and High Market with alternative Inflation rate and alternative Capacity factor (HMIC) scenarios differ from the previous ones in that they consider a capacity factor set at 30 % instead of 35 %. Furthermore, given that WACC is a critical parameter, it is decided to consider the alternative context in which it is 9 %, i.e. 1.5 % higher than in the base scenario (LMW and HMW scenarios). In this way, LM, HM, LMI and HMI scenarios are described in Section 3.2, and the new contexts analysed are described below:

- LMC - Low Market scenario in which the energy selling price is set at 130 €/MWh with capacity factor of 30 %.
- LMIC - Low Market scenario in which the energy selling price is set at 130 €/MWh with annual energy price inflation of 2 % and capacity factor of 30 %.
- LMW - Low Market scenario in which the energy selling price is set at 130 €/MWh with WACC of 9 %.
- HMC - High Market scenario in which the energy selling price is set at 160 €/MWh with capacity factor of 30 %.
- HMIC - High Market scenario in which the energy selling price is set at 160 €/MWh with annual energy price inflation of 2 % and capacity factor of 30 %.
- HMW - High Market scenario in which the energy selling price is set at 160 €/MWh with WACC of 9 %.

By way of example, Figures S11-S12 show the thousand iterations for the HM and LM scenarios, but the same is proposed for all scenarios. Table 7 shows the probability that the NPV is positive in different contexts.

The results of this analysis further reinforce the conclusions previously outlined. In particular, the HM scenarios consistently show higher probabilities of positive NPV across multiple case studies. The highest value is observed in the HMI scenario, where 99.1 % of simulations yield a positive NPV. Even in the most challenging HM context - where the capacity factor is reduced to 30 % - the NPV remains positive in 82.5 % of the cases. The results compared to WACC also confirm the need to evaluate this parameter, highlighting the high profitability in the HMW context of approximately 30 percentage points compared to LMW.

The base HM scenario shows a 93.3 % likelihood of a positive NPV, which decreases to 64.3 % under the LM scenario. While the LM context presents greater risk, it does not lead to a complete deterioration of performance: with a capacity factor of 30 %, the share of positive outcomes falls below half (47.8 %), but rises significantly to 88 % in the LMI scenario, where inflation is included. These results indicate that both the capacity factor and inflation are critical determinants of the project's economic viability.

In summary, LM scenarios present a moderate level of risk, whereas HM scenarios reflect low risk. In cases where inflation and market factors interact, annual inflation emerges as a key influence, suggesting that appropriate mitigation strategies - such as indexing mechanisms - could help manage financial exposure. Lastly, sensitivity to the capacity factor, which could decline due to reduced wind speeds or technical inefficiencies, remains a decisive factor. In situations of lower energy prices or reduced production, moderate inflation can serve as a buffer. However, this must be considered within the broader dynamics of the public energy sector.

Finally, to have a complete economic vision of the project, another valuable tool for the realization of offshore wind plant is the break-even point (BEP) analysis. This method helps to assess the internal dynamics that determine the balance between costs and revenues. In the case of the wind farm study, it is used to identify the minimum energy price at which the NPV equals zero. Table S6 outlines the various case studies developed based on the key variables mentioned above (inflation, net producibility, initial investment, and capacity factor), while Table 8 provides a summary of the corresponding energy sale prices derived for each scenario.

The results of the BEP analysis indicate that the calculated energy prices align closely with the low market scenario, which should therefore be regarded as the limiting condition for the project's feasibility. At the same time, these results reveal substantial variability in the project's economic viability depending on the operational conditions. While the base case (119.65 €/MWh) and the scenario with annual inflation of 2 % (110.80 €/MWh) fall below the LM sales price (130 €/MWh), this does not hold true for all other variables analyzed. In particular, BEP prices remain below the LM level only under modest changes - specifically, a 5 % decrease in net producibility and a 10 % increase in investment costs. When these variations increase to 10 % and 20 %, respectively, the BEP rises to approximately 133 €/MWh.

Among all the variables considered, the capacity factor has the greatest impact. A reduction to 30 % (i.e., −5 % compared to the base case) results in a BEP price of 140 €/MWh, while a further decrease to 25 % (-10 % from the base case) pushes the BEP to 168 €/MWh (+40 % than base case). This latter figure exceeds the High Market price of 160 €/MWh, rendering the project economically unviable without public support.

These findings underscore the critical importance of: (i) accurately assessing the site's wind potential and selecting an optimal location; (ii) maintaining strict control over construction costs, which significantly influence total expenditure; and (iii) implementing revenue stabilization mechanisms. Without these safeguards, the project may prove marginal or even economically unfeasible under certain scenarios.

5. Discussion

Renewable energy sources have profoundly reshaped the energy landscape, not only by transforming the business models of traditional utilities but also by opening new strategic opportunities and actively

Table 7
Risk analysis – Probability of profitability.

	Probability of NPV> 0
Scenario LM	64.3 %
Scenario HM	93.3 %
Scenario LMI	88.0 %
Scenario HMI	99.1 %
Scenario LMC	47.8 %
Scenario HMC	82.5 %
Scenario LMIC	79.5 %
Scenario HMIC	97.9 %
Scenario LMW	67.8 %
Scenario HMW	98.3 %

Table 8
BEP – Selling price.

	Selling price
Base case	119.65 €/MWh
Standard case with annual inflation of 2 %	110.80 €/MWh
Case of a 5 % decrease in net productivity	125.90 €/MWh
Case of a 10 % decrease in net productivity	132.90 €/MWh
Case of a 10 % increase in initial investment costs	126.50 €/MWh
Case of a 20 % increase in initial investment costs	133.40 €/MWh
Case of a 5 % decrease in capacity factor	139.60 €/MWh
Case of a 10 % decrease in capacity factor	167.80 €/MWh

involving citizens in the energy transition. Increasingly engaged as prosumers, citizens are becoming key agents of change - contributing to both energy generation and system management.

Technological innovation has been central to this transformation. Advancements in renewable energy technologies - well documented in the literature (Ahmad et al., 2023; D'Adamo et al., 2023; Pramanik et al., 2020) - have significantly improved performance, scalability, and cost-efficiency. LCOE values confirm that many renewable technologies are now fully cost-competitive with fossil fuel-based alternatives. The results of this study reinforce this trend, with LCOE figures comparable to those reported for similar offshore wind projects across Europe (Martinez and Iglesias, 2022).

Within the European context, the urgency to accelerate renewable deployment is undeniable. Each Member State, and every region within it, is expected to contribute meaningfully toward collective climate and energy goals (Ronchetti et al., 2025). However, the objective is not solely to increase the output of clean energy - it is also to foster a technologically advanced, resilient, and self-sufficient industrial ecosystem. Innovation plays a critical role here, particularly in reducing dependence on imported raw materials, improving circularity, and integrating life cycle assessments into the development and deployment of renewable technologies (Diez-Cañamero and Mendoza, 2023).

Decision-making in the renewable sector involves a complex interplay of technical, economic, and social factors (Zhang et al., 2024; Aparisi-Cerdá et al., 2024). Long-term resource forecasting is crucial - especially given the expanding role of renewables in supporting emerging technologies such as green hydrogen (Bonesso et al., 2025; Wang et al., 2025). Moreover, the positive economic externalities of renewables - ranging from avoided health and environmental costs to their contribution to climate change mitigation - reinforce their strategic value (Zountouridou et al., 2015; Ramalho et al., 2025).

Ensuring economic sustainability remains essential for guiding sound investments (Pires et al., 2022b; Bist et al., 2020). Yet, the inherent volatility of energy markets, evolving technology costs, and the sensitivity of key technical parameters demand continuous, context-specific evaluation (Martinez and Iglesias, 2024; Malleret et al., 2024). In line with previous studies, this research adopts a multidimensional economic evaluation framework based on established financial indicators (Castro-Santos et al., 2018). It also proposes a flexible methodological structure that allows tailored analysis depending on the most influential variables in each case.

The BEP analysis reveals that offshore wind projects can achieve economic viability even in the absence of public subsidies, if energy sale prices remain in line with current market levels. However, this profitability is vulnerable to speculative behaviour, social resistance, and localized opposition - especially in communities near the project sites. In many cases, environmental awareness and sustainability education have not been sufficient to overcome territorial concerns. Therefore, a pragmatic, locally responsive approach is necessary, one that respects the principle of proportionality between energy generation and regional needs.

Against this backdrop, the economic sustainability of offshore wind energy must not be viewed solely through a financial lens. It is a fundamental condition for delivering long-term environmental benefits, stable employment, and industrial innovation. Unlocking the full contribution of offshore wind to sustainable development requires both robust technological foundations and a supportive policy environment. Reducing the WACC through stable regulatory frameworks, targeted incentives, and risk-mitigation instruments is crucial. Ultimately, the integration of innovation and advanced technologies with sound economic planning will be decisive in ensuring the successful deployment of offshore wind as a pillar of the green transition.

6. Conclusions

Achieving global sustainable development goals - particularly SDGs 7 and 13 - requires an accelerated transition toward renewable energy sources. The economic viability of large-scale renewable energy projects is a critical enabler of this transition, influencing the speed and scale at which clean technologies can be deployed.

This study addresses that challenge by building on evidence from a SLR on the economic sustainability of offshore wind energy. It presents an economic feasibility assessment of a proposed 55 MW floating offshore wind farm located off the coast of Toscana, Italy. Grounded in the findings of the SLR, the study applies established financial tools – namely DCF analysis and LCOE - to evaluate the project's long-term viability over its projected 25-year operational lifespan. The main objectives were to determine the lifecycle economic sustainability, outline the cost-benefit profile, identify key economic drivers and sensitivities, and contextualize broader insights from the literature within a region-specific setting.

The results confirm the economic viability of the proposed wind farm under various market conditions. However, profitability remains highly sensitive to energy prices and financing assumptions. Scenarios based on higher energy prices (160 €/MWh) yield significantly greater NPV than those assuming lower prices (130 €/MWh), with NPV ranging from 10.7 million € to 72.8 million €, depending on scenario inputs. The introduction of a 2 % annual energy price inflation rate further improved return projections. The baseline LCOE, calculated at 138 €/MWh, falls within the range observed for comparable offshore projects in the Mediterranean. Nonetheless, the analysis reveals a strong dependency on the WACC, highlighting its influence on financial sustainability.

Sensitivity and scenario analyses indicate that the project is particularly vulnerable to adverse changes in key technical and economic parameters - especially simultaneous increases in investment and O&M costs or reductions in the capacity factor. The energy sales price and the capacity factor emerged as the most influential variables. Break-even analysis showed that a substantial reduction in capacity factor (e.g., a 10 % drop) would necessitate energy prices above 160 €/MWh to maintain viability without policy support.

Overall, the findings underscore the project's potential feasibility under the assumed conditions, while emphasizing the critical role of market dynamics, financing costs, operational efficiency, and site-specific resource potential. These results also reaffirm the value of technological innovation and continuous improvements in design, efficiency, and floating wind technologies in enhancing economic performance and resilience.

Despite its contributions, this study is subject to certain limitations. The analysis focused primarily on economic sustainability, excluding detailed environmental and social dimensions. Moreover, it is based on techno-economic assumptions derived from literature, expert input, and site-specific data, which are inherently uncertain. The study's insights are specific to the Toscana case and may not be directly applicable to other locations with different wind regimes, grid infrastructures, or regulatory contexts. Limitations in the scope and time range of the reviewed literature in the SLR also constrain generalizability.

Future directions should include the evaluation of real-world data from installations in Italy to improve their reliability - particularly regarding system leaks and plant degradation. It is also essential to assess how permitting and authorisation delays can negatively impact project viability, as postponing construction may lead to opportunity costs when the project is otherwise profitable. However, such evaluations must be framed within a pragmatic model, which emphasizes the development of plants appropriately scaled to their surrounding environments. In addition, future research should integrate recent advancements in floating wind technology and projected cost reductions to refine lifecycle cost analysis and improve the accuracy of LCOE projections for the Toscana offshore site. Additionally, refining long-term cost models for O&M and decommissioning, and examining the influence of supply chain evolution and technological innovation on LCOE reduction, represent promising directions for future investigation. A further element of analysis will be to assess how these plants will

interact with the electricity grids, but this challenge is part of a context in which it is essential to produce renewable energy to reduce energy costs in Italy and enable citizens and businesses to be more in line with other European countries. Future research could extend this work by developing integrated sustainability assessment frameworks that include quantitative environmental and social indicators alongside economic ones. Comparative analyses across different Italian coastal regions - or between floating and fixed-bottom technologies in the Mediterranean - could offer valuable insights into location-specific feasibility.

Nevertheless, the study provides several important policy implications. It highlights the need for stable and predictable market frameworks to ensure investment attractiveness in capital-intensive offshore wind infrastructure. The sensitivity to WACC demonstrates that public policies affecting financing conditions - such as risk guarantees, concessional financing, or green bonds - can play a decisive role in supporting economic sustainability. The findings also suggest that revenue stabilization mechanisms or targeted support instruments may be necessary to protect projects from underperformance due to market volatility or lower-than-expected energy yields. Streamlined permitting procedures and accurate site assessments further emerge as strategic priorities to facilitate timely and cost-effective deployment.

Sustainability is a complex challenge that can be achieved with the involvement of citizens, businesses and institutions. Where local industries establish a supply chain, this can make the sector even more competitive. Green energy production is essential, but speculation must be avoided and energy models that guarantee clean energy for neighbouring areas must be supported. Offshore wind energy, although intermittent, can play a decisive role in sustainable development by strengthening national energy independence.

Author Statement

All of the authors (Idiano D′Adamo, Simone Di Leo, Massimo Gastaldi, Ilhan Ozturk, and Umberto Terzi of Bergamo) contributed equally to the writing of the article.

CRediT authorship contribution statement

Idiano D'Adamo: Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Umberto Terzi di Bergamo:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Ilhan Ozturk:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Massimo Gastaldi:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Data curation, Conceptualization. **Simone Di Leo:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The present study was conducted within the framework of the PEACE ('Protecting the Environment: Advances in Circular Economy') project, funded by the 'Fondo per il Programma Nazionale di Ricerca e Progetti di Rilevante Interesse Nazionale (PRIN)', Investimento M4.C2.1.1-D.D. 104.02–02–2022, 2022ZFBMA4 under the European Union – Next Generation EU. The manuscript reflects the views and opinions of the authors, only, who bear full responsibility for them.

The authors would like to thank Pellegrino Guerriero and the Renexia group for the seminar held at Sapienza University, during which various points for reflection were presented that are useful for understanding the development of offshore wind power in Italy, but also globally.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.egyr.2025.10.003.

Data availability

Data will be made available on request.

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