World Development Sustainability 5 (2024) 100184

Contents lists available at ScienceDirect

World Development Sustainability

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

An economic analysis of tidal energy to support sustainable development

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A R T I C L E I N F O

Keywords:
Economic analysis
Profitability
Renewables
Tidal energy
Sustainable development

A B S T R A C T

Decarbonization of the energy sector, requires a strong expansion of renewable energy, which combined with effective and efficient use of resources, enables the development of models based on the green economy. Tidal energy, which is currently underutilized, can contribute to this change by providing affordable and clean energy, thus contributing to sustainable development. This work evaluates the economic dimension of sustainability and provides a profitability analysis related to a 1 MW plant located in central Italy. The methodology consists of a technical framework, geared toward quantifying the energy potential from that plant, and economic models based on indicators such as Net Present Value (NPV), Levelized Cost of Energy (LCOE) and Discounted Payback Time (DPBT).

The results show that the plant turns out to be profitable in the base case (NPV = 573 k€ and DPBT = 21 years) and policy interventions, which see the use of capital grants and subsidies, change the results to NPV ranging between 338 and 1287 k€ and DPBT between 11 and 15 years. However, alternative scenarios indicate that the variables that most impact economic outcomes are changes related to energy selling price and capacity factor. The LCOE in the different scenarios varies between 49.4–89.8 €/MWh. The implications of this work define that tidal energy supports the energy transition to sustainable development and that the mix of technical, market, and political factors must be considered in policy decision making.

1. Introduction

The application and deployment of renewable energy for sustainable development can take place at the local level [1], country level [2], of a continent [3] or comparing different countries [4]. Human development and trade openness are positively associated with sustainability [5], but the challenge of ecological transition is also related to the concept of resource circularity [6–8] and sustainable community [9–11]. The pandemic period had consequences on ocean pollution due to mismanagement practices on waste [12], which, however, already characterized this natural place [13]. The risks to places such as forests and oceans are well underscored by some analyses [14], and added to this is the fact that storm surges could cause harm to the community by impacting public opinion [15].

However, the ocean is not only a resource to be protected, because of what humans are able to do, but it can provide resources that foster regional economic growth [16]. Ocean renewable energy is considered one of the most important clean energy sources [17] and supports the ambitious European project toward climate neutrality, but the same is also evident in other spatial contexts [18,19]. Specifically, tidal energy has significant potential to contribute to the global energy mix, offering solutions to mitigate the impact of climate change [20]. This form of energy, by harnessing tidal variations, can provide a reliable and lasting source of electricity. However, the need to carefully assess the environmental and social impacts of integrating such technologies into marine ecosystems and local communities is crucial to ensure public acceptance and regulatory approval of tidal energy projects [21]. Technology development has the potential to make them more competitive [22] and some studies analyze tidal stations and technologies that allow tidal variations to be harnessed to generate power [23,24]. In particular, the most promising installation areas for harnessing wave energy and tidal currents have been identified [25]. The focus on energy conversion devices paid attention to technologies [26] and the different configurations [27,28] geared toward maximizing energy efficiency, minimizing environmental impact with the goal of improving hydrodynamic performance and ensuring the structural survival of

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https://doi.org/10.1016/j.wds.2024.100184
Received 26 June 2024; Received in revised form 2 September 2024; Accepted 27 September 2024
Available online 6 October 2024

plants in adverse marine conditions. Similarly, such plants should be integrated with coastal management [29] in order to also contribute to coastal protection and climate change mitigation [30].

The feasibility of integrating tidal power has been highlighted through several key aspects. First, the identification of suitable sites for the installation of tidal power plants that is based on a detailed understanding of maritime dynamics and local specificities [31–33]. This targeted selection ensures that each plant is optimized for the environmental conditions present, maximizing energy efficiency and minimizing negative impacts on the marine ecosystem [34,35]. Second, the design and configuration of tidal turbine arrays represent an additional level of optimization [36]. Third concerns the management of the energy produced, through energy storage and flow regulation systems in the power grid, which is critical to aligning production with consumption [37]. Finally, the last aspect concerns the economic analysis, which reveals that despite the initial challenges related to implementation costs, the long-term benefits in terms of reduced dependence on fossil fuels, decreased carbon emissions, and stabilized energy prices are significant [38].

One of the barriers to the commercial development of such technologies is the high cost and environmental impact that should be determined by life cycle analysis [39]. In addition, more focus is needed, as the fragmentation of R&D investment risks weakening the development of the sector [40]. Improvements in design and on maintenance strategies are central to lowering operational costs and increasing the efficiency of tidal installations [41]. The advancement of research in tidal power significantly underscores the importance of economic considerations in the development of this renewable technology. Some studies show benefits such as predictability and contribution to security of energy supply, but economic issues still pose considerable challenges to its large-scale implementation [42,43]. The Levelized cost of electricity (LCOE) varies for different installations of Wave Energy Converters (WEC) and the Wave Dragon, which stand out for their low cost of energy conversion compared to other technologies such as Pelamis and AquaBuOY [44]. The literature highlights the need for the promotion of new designs and cost-sharing practices, which is found to be instrumental in the decision-making process [45].

Wave development relies on sound economic analysis to provide information in terms of policy, to guide industry investment, and to direct progress in research and development [46], with the goal of identifying the correct balance point between subsidies and learning rates [47]. The aim of this work is to propose a technical-economic model and provide results for assessing the feasibility of installing a specific tidal power plant in the Italian context. The research presents a mathematical model that aims to predict potential energy production and its economic effects. This model establishes a relationship between the phenomenon (the significant wave height) and the outcomes (an energy capacity factor). The economic analysis is based on various economic indicators, such as Net Present Value (NPV), LCOE, and Discounted Payback Time (DPBT), and provides assessments in several scenarios in which the selling price of energy, the investment cost, inflation and the capacity factor of the energy produced are made to vary. In this way, these analyses can define whether tidal energy can support the achievement of the sustainable development goal and can provide guidance to the various stakeholders in order to facilitate its deployment in the Italian context as well.

2. Materials and methods

The issue of renewable energy is a key pillar in achieving sustainable development and transitioning to an economy less dependent on fossil fuels [48–50]. Technologies that harness marine energy, including wave and tidal energy, offer untapped potential that can contribute significantly to the diversification of the global energy mix as outlined in the previous section. In this study, the feasibility of installing a 1 MW wave energy plant (Eco Wave Power) in the port of Livorno was explored. Livorno is an important port city on the western coast, facing the Tyrrhenian Sea and located in central Italy. Italy has good potential in marine energy that should be better exploited [51,52]. The methodology adopted consists of several stages, from the collection of initial data to the analysis of the technical and economic performance of the plant and is based on a multidisciplinary approach. The main characteristic that makes the port of Livorno an optimal choice for the installation of a tidal plant lies in its characteristics as a port devoted to innovation and by its significant maritime traffic. These factors, combined, offer a not inconsiderable potential for energy generation: the natural wave motion, combined with the artificial wave motion generated by the water displacement of large ships, can be exploited to produce energy in an alternative way. The energy generated by the tidal power plant can be integrated into the port's electrical infrastructure, providing sustainable power for docked ships, thus further reducing their emissions.

This section is divided as follows. After presenting the adopted technology (section 2.1), we will proceed to describe the economic model used (section 2.2). Section 2.3 shows data analysis related the technical end economic aspects.

2.1. The technology adopted

The installation of an onshore tidal power plant in or near Livorno's docks identifies a strategic choice of considerable interest. The decision to move toward Oscillating Surge Wave Energy Converter (OSWEC) technology represents a promising approach to harness wave energy, and Livorno offers the ideal context for implementing such technology. It harnesses wave motion to activate a high-efficiency mechanical conversion system that is particularly well suited to the marine conditions present in Livorno, which are characterized by a wave regime that can ensure consistent and significant energy production, due in part to high vessel traffic. Integrating the system into or near existing docks not only optimizes the use of space, but also helps to enhance the port area. Unlike traditional offshore systems, which have encountered numerous drawbacks, such as high installation, maintenance and grid connection costs, reduced reliability due to extreme marine conditions, difficulties in insurance, and negative environmental impacts, the technological system designed for the Port of Livorno called Eco Wave Power (Eco Wave Power - Wave Energy Company) overcomes these issues. By installing its systems in onshore and nearshore environments and attaching them to marine structures such as breakwaters or docks, this technology harnesses the energy potential of waves in a more sustainable way. Studies have confirmed that onshore technologies, such as those adopted by Eco Wave Power, have significantly higher survivability and are more economical than offshore solutions [53].

The Eco Wave Power system converts the upward and downward movement of waves into clean energy through a process involving floats that compress and decompress hydraulic pistons. These transmit a biodegradable hydraulic fluid to accumulators on land, where pressure is generated. That pressure drives a hydraulic motor and generator, transferring electricity to the grid via an inverter in a closed circular system. The system starts producing electricity from wave heights of 0.5 meters and includes a storm protection mechanism that totally raises the system. Advantages of Eco Wave Power include cost efficiency, with significantly lower construction and production prices than offshore competitors, high reliability with most of the system positioned on land, and mechanisms floating in the water protected from an aggressive marine environment. In addition, the environmental impact would be minimal, since the system does not connect to the seabed. This makes this technology appropriate in wave power generation in this specific context.

2.2. Methodology

The economic instruments used, which are considered to be the most suitable for assessing the effectiveness and sustainability of the project in the long term, are the NPV, LCOE and DPBT [54,55]. The NPV is widely used in the literature to assess the profitability of an investment. The LCOE expresses the average cost per unit of energy produced, incorporating all costs incurred during the useful life of a plant (initial, operating, maintenance, and disposal costs). It is essential for comparing the costs of different energy technologies and determining which one is the most economical or cost-effective per unit of energy produced. The DPBT is a financial indicator that measures the time required to recover the cost of an initial investment through future cash flows, discounted to account for the time value of money. This helps to assess how quickly an investment can become profitable, considering the risk and cost of capital. These tools provide a satisfactory overview in comprehensiveness and detail of the economics of a project, allowing investors and decision-makers to accurately assess the potential for economic return and associated risks. Initially, the focus was on collecting essential data on the costs and performance of the plant. Integrating the data collected from company presentations with information from industry studies enabled the construction of a more robust and reliable model for analysis. This holistic approach ensured a more complete and detailed understanding of the economic dynamics and expected performance of the plant, considering not only the data provided by the company but also perspectives and comparisons derived from the broader context of the renewable energy sector.

2.3. Data Analysis

After outlining the economic and technical framework of the Eco Wave Power plant, attention shifted to analyzing the marine conditions of the site chosen for installation. To obtain accurate and reliable data, a valuable resource was used: the Copernicus site, a European Union program that provides satellite data and Earth observations, offering access to global environmental information. From the site, a dataset was extracted (Dataset Descritption – Copernicus Marine MyOcean Viewer) particularly relevant to our study, containing hourly spectral significant wave heights for the period from July 2021 to February 2024. This preliminary analysis allowed us to identify key trends and variations in wave behavior in the Port of Livorno by obtaining an immediate visual representation of the trend in mean significant wave heights (the analysis for November 2023 is shown as an example, Fig. 1).

The use of hourly data and their distribution over time offered the possibility of modeling plant performance with a satisfactory level of detail. This approach allowed for more precise verification of the plant's energy production by considering variations in the energy capacity factor related to wave height and strength. In addition, the analysis provided valuable insights into the times of the year when the plant could operate below its optimal capacity, due to unfavorable marine conditions, and those when, on the contrary, higher energy yields could be achieved.

The next step was to define a model capable of relating wave height to plant capacity. The mathematical model was developed to describe the relationship between the significant average wave height (x) and the plant capacity factor (y). Specifically, the model was structured as follows:

- For waves of height less than 0.5 meters ($0 \leq x < 0.5$) -

in this wave height range, the plant maintains a constant capacity factor y of 0%. This is since waves of this height do not allow the plant to work.

- For waves with a height between 0.5 and 1 meter ($0.5 \leq x < 1$) -

in this range, the capacity factor y of the system was assumed to increase linearly with increasing wave height, starting from 30% at 0.5 meters to 100% at 1 meter.

- For waves with a height of 1 meter or more ($x \geq 1$) –

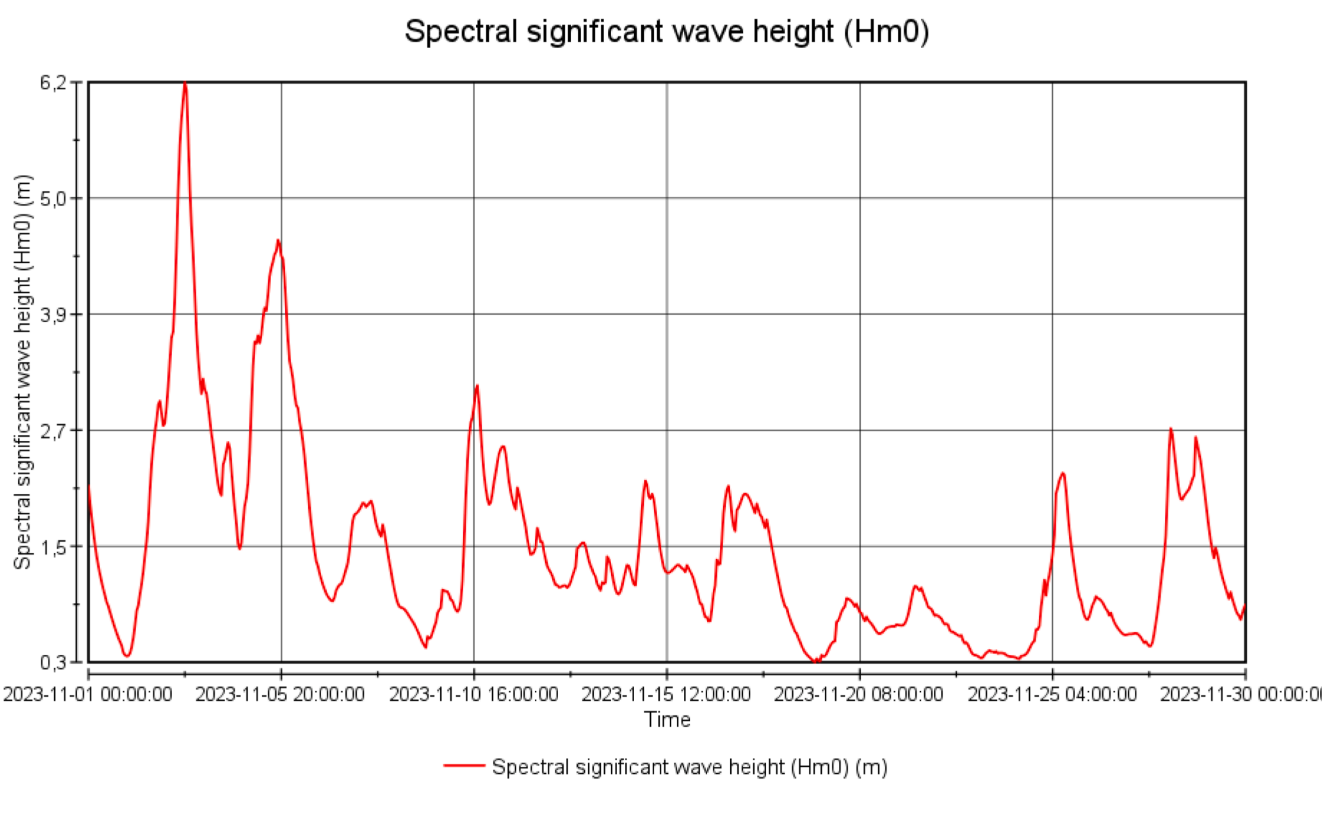

Fig. 1. Tide chart for November 2023.

when the wave height reaches or exceeds 1 meter, the capacity factor of the plant y is kept constantly at 100%. In this situation, the model assumes that the plant can operate at maximum capacity.

This model tries to plausibly model the behavior of the plant with respect to changes in wave heights and provides a solid basis for predicting and calculating the energy efficiency of the plant under different marine scenarios. The calculated efficiencies for each day were displayed by color grading from red to green, where red indicates the lowest efficiencies and green the highest. This color choice makes it possible to quickly identify the periods of highest and lowest energy productivity of the plant. The analysis covered the years 2021, 2022 and 2023 and the early months of 2024. The analysis for 2023 is shown as an example (Table 1).

The analysis revealed some crucial information. First, seasonality only plays a significant role in terms of negative impacts on energy production: the summer period, marked by less high and less energetic waves, turns out to be the one in which the plant generates the least energy. In addition, the analysis confirmed that the waves in these areas tend to be lower in height than in other oceanic settings, implying that to optimize energy harvesting in these areas, plants must be able to convert even the smallest waves into energy.

The proposed analysis was obviously not limited to the evaluation of energy production alone but also included the calculation of economic indicators. The LCOE calculation for the Eco Wave Power plant in the Port of Livorno was carefully structured around a 35-year projection, divided into five years dedicated to construction and 30 years of operation. Investment costs were concentrated at year zero. Annual operating costs were estimated to be a percentage of the initial investment, representing a significant portion of the total costs and reflecting the need for ongoing maintenance and management of the plant to ensure its efficiency over time. The formula used to calculate LCOE places these discounted and cumulative investment and operating costs in the numerator, while the total energy produced is placed in the denominator, which undergoes a percentage of annual degradation. Below, formulas for NPV, LCOE and DPBT are proposed:

$$\mathrm{NPV} = \sum_{t=0}^{34} \frac{\mathrm{CFI_t} - \mathrm{CFO_t}}{(1+r)^t}$$

Table 1
Technical analysis for 2023.

Days	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0%	55%	12%	100%	0%	0%	96%	59%	44%	0%	68%	100%
2	30%	42%	15%	100%	33%	0%	95%	96%	0%	0%	81%	100%
3	22%	15%	6%	53%	5%	0%	53%	87%	0%	0%	100%	90%
4	0%	60%	0%	8%	0%	6%	46%	100%	0%	19%	100%	11%
5	6%	22%	55%	0%	0%	0%	11%	100%	0%	0%	100%	67%
6	15%	0%	92%	0%	0%	0%	20%	100%	0%	0%	100%	84%
7	0%	1%	100%	11%	0%	0%	0%	97%	0%	0%	98%	14%
8	58%	1%	100%	11%	0%	0%	0%	15%	0%	0%	94%	12%
9	100%	1%	100%	0%	0%	4%	0%	0%	0%	0%	54%	20%
10	100%	0%	100%	0%	41%	0%	0%	0%	0%	16%	94%	97%
11	77%	0%	100%	14%	84%	0%	0%	0%	0%	0%	100%	98%
12	68%	1%	98%	73%	82%	0%	45%	0%	0%	0%	100%	91%
13	65%	0%	56%	77%	23%	0%	20%	0%	0%	0%	100%	89%
14	67%	0%	95%	100%	0%	0%	25%	0%	0%	14%	100%	100%
15	85%	0%	100%	100%	31%	6%	0%	0%	0%	100%	100%	73%
16	100%	0%	34%	78%	78%	22%	11%	0%	10%	41%	91%	0%
17	100%	0%	0%	25%	84%	0%	0%	0%	11%	0%	100%	0%
18	100%	0%	19%	0%	18%	0%	0%	0%	32%	35%	69%	0%
19	100%	29%	1%	0%	0%	21%	0%	0%	80%	64%	22%	0%
20	85%	16%	0%	13%	0%	43%	34%	0%	35%	100%	64%	20%
21	60%	0%	0%	0%	0%	22%	57%	0%	15%	100%	73%	94%
22	23%	0%	1%	0%	0%	27%	87%	0%	80%	97%	57%	100%
23	24%	0%	0%	8%	0%	27%	61%	0%	100%	51%	3%	100%
24	16%	36%	11%	82%	0%	26%	42%	0%	63%	97%	22%	99%
25	0%	34%	78%	100%	0%	3%	73%	0%	0%	100%	97%	41%
26	12%	37%	100%	51%	0%	0%	100%	25%	0%	100%	69%	29%
27	18%	54%	100%	0%	0%	4%	61%	25%	0%	100%	50%	3%
28	3%		55%	0%	0%	21%	0%	100%	0%	100%	100%	0%
29	0%		15%	0%	0%	0%	0%	100%	0%	86%	91%	0%
	Working hours											
	450.00	147.00	446.00	295.00	174.00	137.00	340.00	256.00	168.00	332.00	630.00	478.00
	Average monthly capacity factor											
	46%	15%	50%	35%	16%	8%	32%	31%	16%	42%	79%	53%
	Average annual capacity factor											
	35%											

$$LCOE = \frac{\sum_{t=0}^{34} \frac{CFO_t}{(1+r)^t}}{\sum_{t=0}^{34} \frac{E_{out} \cdot (1-d_{Et})^t}{(1+r)^t}}$$

$$\sum_{t=0}^{DPBT} \frac{CFI_t - CFO_t}{(1+r)^t} = 0$$

where CFO = cash outflows; CFI = cash inflows; E_{out} = annual energy production; r = opportunity cost of capital; d_{Et} = annual degradation rate of plant production and t = the period of reference.

The main economic and technical inputs used for our model are applied to a plant with a capacity of 1000 kW. This choice is based on the plant's ability to generate, theoretically, up to 8,760,000 kWh annually. In addition, an annual degradation factor of 0.8% was considered, reflecting the gradual decrease in the plant's generating capacity due to wear and aging of components. Regarding the initial investment, capital of 1.4 million € was required for the installation of the plant. Annual operating costs, considering operation and routine maintenance, were estimated to be 15% of the initial investment, thus resulting in 210,000 € annually. It also assumes a plant capacity factor of 35% equal to the average capacity found in the technical analysis, an energy selling price set at 0.11 €/kWh, and an initial investment concentrated entirely in year zero, thus outlining the operational and financial conditions under which the plant is expected to operate.

As previously defined, the lifecycle of the plant was designed equal to 30 years and the time of realization was equal to 5 years. For the financial analysis, a discount rate of 5% was used. Finally, in this initial scenario, the analysis incorporated an annual inflation rate of 3%.

3. Results

The objective of this study is to provide an assessment of the economic feasibility of a tidal plant that has a capacity of 1000 kW located in the port of Livorno. Initially, the results related to the base case scenario (section 3.1) are proposed, and next are the alternative case studies that propose sensitivity, scenario and risk analyses in addition to the break-even point (BEP) analysis (section 3.2). Finally, some alternative political scenarios are analyzed (section 3.3).

3.1. Baseline scenario

Starting from the economic model and the economic and technical inputs proposed in Section 2, the base case scenario can be analyzed obtaining the following results:

- NPV is equal to 573 thousand €;
- DPBT is equal to 21 years;
- LCOE is equal to 70.55 €/MWh.

The base scenario sees an economic feasibility of the project reaching a NPV of 572.9 k€, which thus indicates that in addition to the environmental benefit related to the development of renewable sources replacing fossil sources, important economic benefits are also obtained from this green economy project. The DPBT of 21 years is not a low value and is equal to two-thirds of the useful life of the project. So, in the worst-case scenario that the cut-off period is set equal to 30 years, there would be economic benefit. Thus, in the assumption that investors do not need to return from the investment in a very short period of time, it is also possible to show cost-effectiveness considering this indicator. Finally, the LCOE of 70.55 €/MWh appears to be in line with other renewable sources [48,56] indicating how this energy source can also contribute to a country's energy security and energy independence. Furthermore, it is evident how its increased deployment could positively impact project costs through experience economies.

3.2. Alternative scenarios

To give robustness to the results obtained, multiple analyses were conducted in which alternative scenarios are evaluated.

3.2.1. Sensitivity analysis

Initially, sensitivity analysis was proposed in which one variable is varied at a time – Table 2. The two critical variables selected were the energy selling price and the capacity factor. Regarding the first variable, an input value of 0.09 €/kWh was considered. This change in the selling price, while having no effect on the value of the LCOE, has an impact on the financial results of the project. Specifically, the NPV has decreased, standing at -585 k€, thus indicating that the project is no longer profitable. A reduction of 0.02 €/kWh has a decisive impact on the project's economic viability. The DPBT is also consistent with the NPV and within the 30 years (equal to the useful life) the investment is not recovered. These variations confirm that the selling price of energy is strategic in economic analyses of energy projects. In addition, it is the variable that has the greatest impact on revenues, particularly in scenarios with no public incentives and/or avoided costs in the bill if the investor produces the energy for self-consumption. Regarding the second variable, in the base case scenario, the capacity factor values were set conservatively at 35% to demonstrate the robust generating capacity of the plant even under suboptimal conditions. However, to assess the maximum potential of the plant, a situation was considered in which the plant operates with a capacity factor increased to 40%, thus still assuming that it does not operate above average most of the time. This case study, compared to the previous one, is optimistic and thus all indicators show an improvement that is also significant. The NPV increases to 1.5 M€, while the DPBT decreases to 15 years (thus equal to half the useful life of the project) and the LCOE to 61.7 €/MWh. Thus, these results confirm how this technical variable, which is directly influenced by the maritime conditions in which the plant is operating, is crucial in determining the economic effectiveness of the installation. Therefore, an accurate assessment of marine conditions during the planning and design phase of the energy project is crucial. On the cost side, the investment cost was varied and a pessimistic scenario of 1.6 million € was considered. This results in a not very impactful reduction on the NPV, which remains positive and equal to 373 k€, while the DPBT increases to 25 years. Likewise, the LCOE almost reaches the value of 73 €/MWh, which is still an acceptable value in terms of competitiveness. Finally, given the impact that could be generated by inflation that acts more on the selling price of energy than on costs, a case study without inflation was considered and is labeled as pessimistic. The NPV decreases and becomes negative in this context as well and is found to be -141 k€, the LCOE decreases becoming 49.4 €/MWh and finally the DPBT again conforms to the NPV with a non-recovery value over the lifetime. It is worth pointing out that in this case study, the LCOE indicates a higher cost-effectiveness of the project, but it is nevertheless objective that not including inflation in the cost estimates is an underestimate that also turns out to impact this indicator.

Table 2
NPV, DPBT and LCOE.

Scenarios	NPV (€)	DPBT (years)	LCOE (€/MWh)
Baseline	572,939	21	70.55
Sensitivity analysis - Energy selling price	−584,978	>30	70.55
Sensitivity analysis - Capacity factor	1481,946	15	61.74
Sensitivity analysis - Investment costs	372,939	25	72.99
Sensitivity analysis - No inflation	−141,850	>30	49.42
Scenario analysis	159,754	28	61.74
Political scenario (capital grants)	992,939	15	65.44
Political scenario (capital grants+subsidies)	338,297	13	77.26
Political scenario (subsidies)	1286,851	11	89.82

3.2.2. Break-even point analysis

Given the results obtained in the sensitivity analyses, it seems appropriate to conduct the BEP analysis, which determines the conditions under which total plant costs equal the revenues generated. This analysis is found to be particularly useful in the context examined considering that in some cases a change in the sign of the NPV has been shown. In the context of the Livorno port scenario, regarding the analysis of the selling price, the BEP calculations show that this value is 0.10 €/kWh and thus confirms the previous value that ranged between 0.09 and 0.11 €/kWh. Regarding the capacity factor, unlike the sensitivity analysis, a pessimistic context must be evaluated, and the BEP value identifies 32%. This break-even analysis provides a clear and detailed picture of the profit thresholds for the plant, highlighting the room for action available in terms of both price and operating capacity. With this data, plant operators can make informed decisions on how to optimize operations and pricing strategy, ensuring the long-term success of the project. In addition, BEP analysis helps identify potential risks and develop strategies to mitigate them, thereby improving the financial and operational resilience of the plant in the dynamic environment of the Italian energy market [57,58].

3.2.3. Scenario analysis

Further analysis can be conducted by scenario analysis, in which multiple variables were made to vary simultaneously. Like what has been proposed previously, variations from the economic model and the tidal analysis model were integrated. Compared to the base scenario, which includes inflation, in addition to considering an energy selling price of 0.09 €/kWh, a capacity factor of 40% was set considering the data used in the sensitivity analysis. Here the opposite effects of the changes in the two variables result in a reduction in NPV that turns out to be 160 k€ and a DPBT that increases at 28 years. The LCOE does not change compared to the case study analyzed earlier, as the capacity factor allows for an increase in the amount of energy produced and consequently the denominator increases – Table 2. An additional aspect that should be brought out is the effects of the project on the local context. In fact, the energy produced over the lifetime amounts to an average of 2,735,523 kWh per year, and considering the data provided by ARERA in which for Toscana the consumption of an average household is 200 kWh per month, it shows that the energy produced could meet the annual energy needs of about 1140 households.

3.2.4. Risk analysis

Finally, to consolidate the results obtained with the base case, the risk analysis was conducted in which the critical variables were made to vary simultaneously, and a probability value was assigned to the event. One thousand iterations were conducted, and the respective mean values and standard deviations were proposed for the following variables: price of energy sold (0.11 €/kWh and 0.02 €/kWh), capacity factor (35% and 5%), and initial investment (1.2 M€ and 200 k€) – Fig. 2.

The results show that the NPV is positive in 74.9% of the case studies, testifying to a fair reliability and attractiveness of the project. Analyzing the distribution of positive results in more detail, it was found that there is a significant concentration of cases in the NPV ranges between 0 and 2000 k€ where about two-fifths of the potential values result (42.7%).

3.3. Alternative political scenarios

The last step in the numerical process of this work was to assess the impact of alternative political scenarios. We opted to consider three distinct incentive instruments:

- Scenario (capital grant) with 30% capital grant on the initial investment cost.
- Scenario (capital grant+subsidies) with 30% capital grant on the initial investment cost and subsidies equal to 0.1305 €/kWh.
- Scenario (subsidies) with subsidies equal to 0.1764 €/kWh.

In fact, the opportunity to obtain subsidies from institutions through capital grants equal to 30% on the initial investment was considered, a measure deemed suitable in agreement with two managers (both with ten years of international experience) interviewed on the topic. This approach currently used in the Italian context for other renewable projects seems to be suitable for a pilot project. The results, related to alternative policy scenario (capital grant) are promising as the NPV is

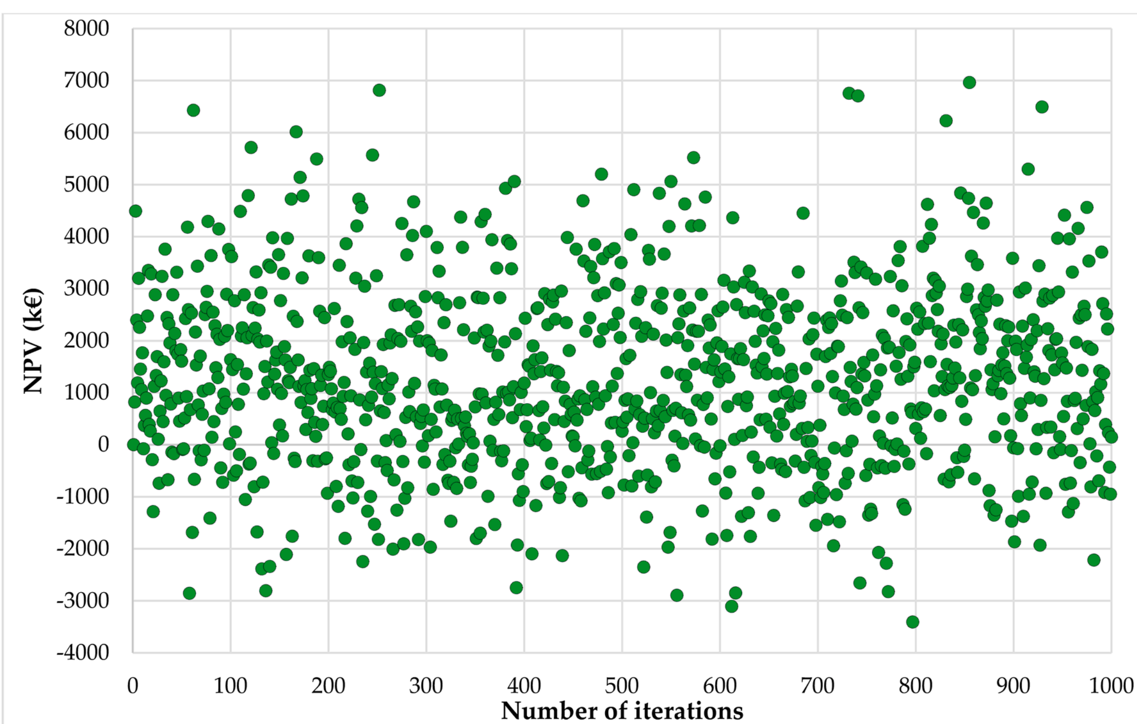

Fig. 2. Risk analysis - Baseline scenario.

almost doubled reaching the value of 992.9 k€ and for the LCOE a reduction of about 5 €/MWh occurs obtaining a value of 65.4 €/MWh – Table 2. This value indicates potential competitiveness, especially considering that the plant uses innovative technology in a high initial cost context. Finally, a 6-year reduction leading to a 15-year output is also highlighted for the DPBT. The repetition of a risk analysis has been integrated to assess the effects of the capital subsidy (Fig. 3). Thus, the only change concerns the introduction of this new parameter. The results show that the number of case studies in which NPV is positive increases by more than ten percentage points (85.4%) and the NPV is always mainly concentrated in the 0-2000 € range for about two-fifths of all values (44.7%).

However, during the development of this project, the Italian government approved the FER 2 Decree, which provides incentives for tidal power generation plants. Specifically for the sector composed of i) tidal, wave and other marine energy and ii) offshore floating photovoltaic the total quotas available for the period 2024-2028 are 200 MW. It is necessary to complete the investment within 3 years and incentives are provided for 20 years. For this form of energy, there are no constraints on the size that is financed, and the benchmark feed-in tariff is 180 €/MWh. Applicants must offer a percentage reduction on the reference tariff, however, not less than 2%, and this percentage is considered in this work. In addition, since the incentive can be combined with the capital grant at 40%, 26% is also deducted from the tariff and as an approximation a value of 130.5 €/MWh is considered. Thus, the assumptions of this alternative policy scenario (capital grant+subsidies) were as follows differently from the previous context: i) capital grant was set at 40% on the initial investment cost; ii) the subsidies were assumed equal to 0.1305 €/kWh; iii) the investment and construction costs were increased by 30% since there is a need to complete the project in a shorter time; iv) project implementation time equal to 3 years and useful life time was set at 20 years; and v) the energy selling price was fixed equal to 0. In addition, while in the previous scenario the selling price varied due to inflation in this one the tariff update is considered to occur by a value of 1% (equal to the difference between what was assumed in this study and the 2% mentioned in the Decree).

The results show that the policy choice with subsidies combined with capital grant turns out to be less profitable. Analyzing the factors that distinguish the scenarios, the subsidy provided is greater than the selling price but this occurs in the first years when there is project operation. In fact, then the different effect of inflation determines that the subsidy impacts less than the tariff. These aspects also prevail compared to a higher capital grant rate (Table 2). The NPV is slightly lower than that obtained in the base case and is 338 k€. It is also shown to be about one-third of the value for the previous policy scenario. The DPBT is reduced compared to both baseline scenarios, with a value of 13 years. This result is thus derived from the new policy proposal that tends to increase profit margins in the first operating years. The LCOE increases to 77.26 €/MWh due to higher investment costs. As for the risk analysis, compared with the previous alternative policy scenario, the critical variable selling price is no longer present and the incentive tariff is not made to vary – Fig. 4. The results indicate that profitability is verified in almost all scenarios (99.9%) and that the value between 0 and 2000 k€ covers 99.6% of these case studies.

Finally, it was considered useful not to combine the two policy interventions. Thus, the capital grant instrument is excluded and only the subsidy, assumed to be 0.1764 €/kWh (subsidies), was considered. The correction factor of 1% on the incentive tariff over the years was also considered in this context. The results are very different from the previous ones, and this scenario is the most advantageous among the policy instruments considered. This effect depends on the percentage reduction that applies to the subsidy when it is combined with the capital grant and the investment costs of the project. The NPV is about 1287 k€, which is double the value of the base case. The DPBT is reduced to 11 years as economic returns are intensified in the early years of the project life and finally the LCOE becomes 89.82 €/MWh as the absence of the capital grant due to higher investment costs that are not mitigated by the presence of the capital grant. Regarding the risk analysis in this context the number of case studies where NPV is positive is worth 91.6% less than in the capital grant+subsidies context but more than the other contexts (Fig. 5). Moreover, 75% of the values are concentrated in the range between 0 and 2000 k€. Thus, the presence of subsidy increases profitability, but the absence of capital grant determines that the potentially pessimistic effect on investment costs results in case studies

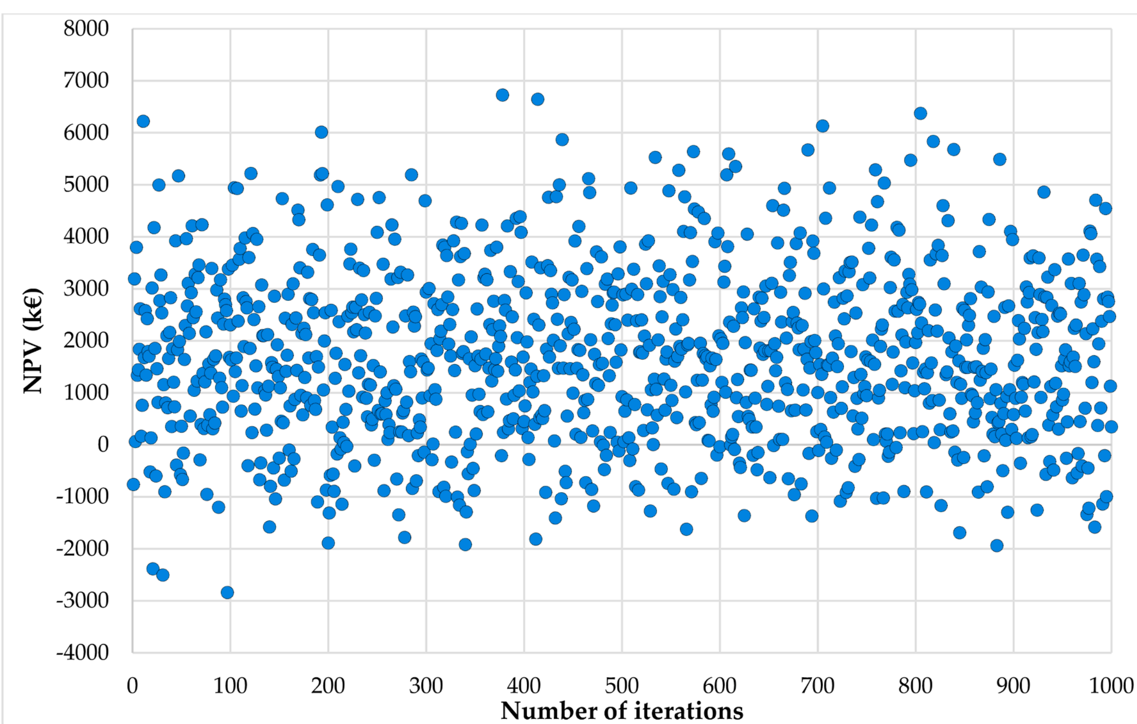

Fig. 3. Risk analysis - Alternative policy scenario (capital grant).

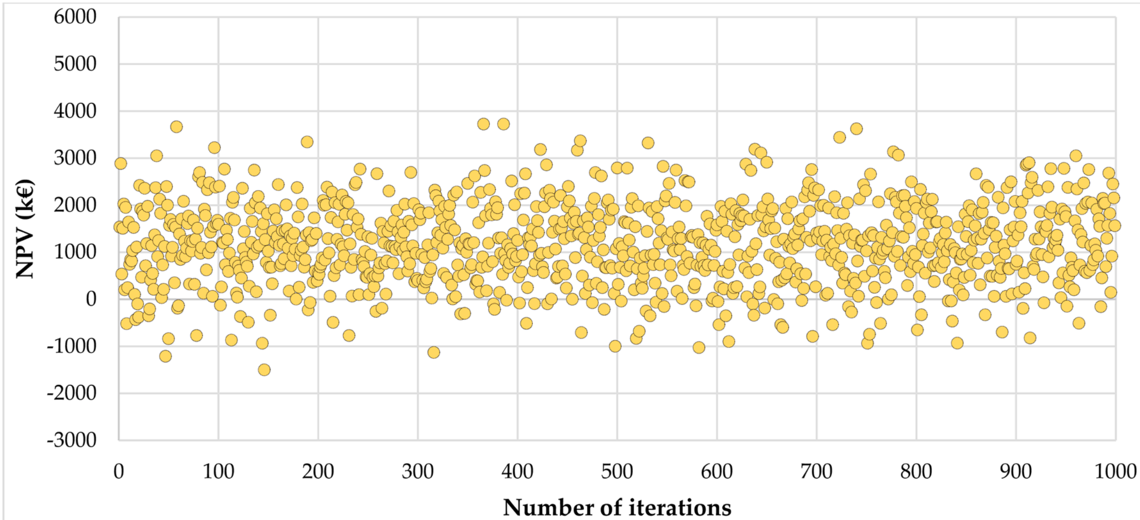

Fig. 4. Risk analysis - Alternative policy scenario (capital grant+subsidies).

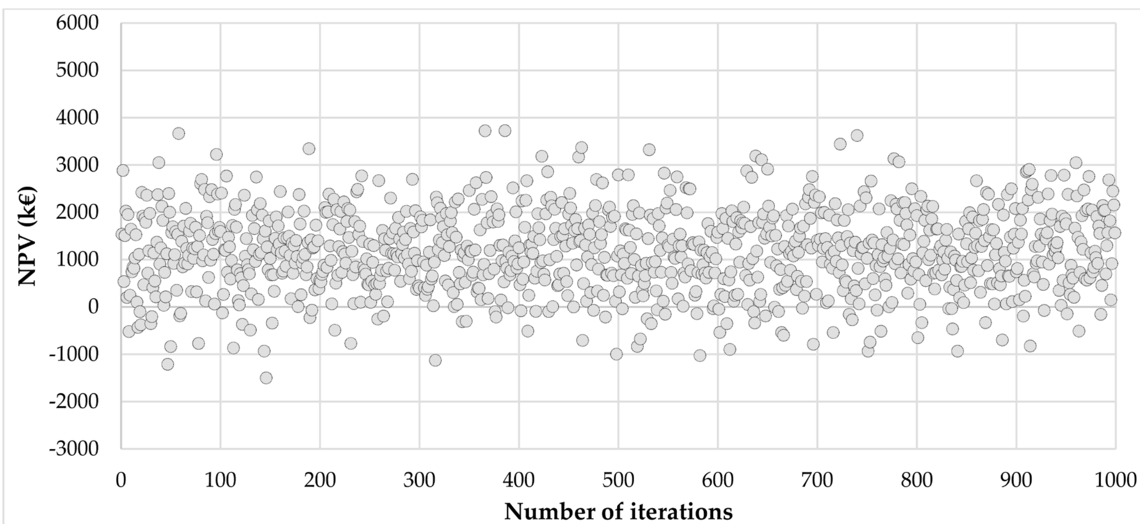

Fig. 5. Risk analysis - Alternative policy scenario (subsidies).

where NPV is lower.

4. Discussion, Policy implications and Limitations of the research

The results obtained can be compared with the literature but are highly dependent on where the plant was located. From this comparison there are works in which profitability is verified and others in which it is not. Thus, it follows that operating conditions and different techno-economic variables identify economic outcomes. Some analyses propose multiple indicators: LCOE varying between 0.10-0.15 €/kWh, NPV between -150 and 250 M€, and the DPBT between 7-12 years [55]. There are several analyses that show unprofitability of plants but also propose LCOE in order to identify cost structure and competitive margins: NPV of -223 k€ with LCOE of 0.421 €/kWh [59], NPV varying between -143 and -137 €/MWh with LCOE of 174-200 €/MWh [60]. The literature places great emphasis on the LCOE indicator, and the results obtained in this work tend to be more confident than in other analyses: 513 €/MWh [61], 0.2254-0.9427 $/kWh [62], 147 €/MWh [63], 165-204 €/MWh [64], 0.15 €/kWh [65], 0.125 €/kWh [66] and 110-150 €/MWh [67]. Other results, however, show more positive results such as those shown in this study: LCOE of 60-100 €/MWh [57] and NPV of 5.5 M€ with PBT of 8 y [68]. However, it can happen that the results can be in line but also more negative as in the LCOE values obtained in other analyses: 70-140 €/MWh [46].

This work evaluated one of the three dimensions of sustainability. From an environmental point of view, it emerges that as always even renewable sources during their entire life cycle may release some emissions however their comparison with fossil sources leads to a reduction in environmental impact. Similarly, public attention to renewable energy should translate into broader public support. Where installations do not alter the existing or are located in areas further away from homes theoretically opposition phenomena should be less. Additional social benefits are related to the domestic industrial development of the sector, which could serve the national territory, but could also convey its business abroad. Thus, the development of renewable energy requires local industrial development to produce such materials so as not to create foreign dependencies that would over time reduce the benefits. However, this work has the limitation that it does not evaluate these two dimensions, but focuses only on the economic one. Multiple case studies are provided that also looked at policy contexts in which there is convergence on the convenience of these facilities. The first policy implication of this work is that this energy source can support a country's energy independence. The second aspect concerns fostering pragmatic models in which there are demands to conduct inclusive sustainability analyses of the three dimensions and information campaigns on citizens to increase their awareness. The third context concerns the comparison of policy instruments that can facilitate the implementation of these projects. What emerges is that there is a need to monitor the relationship between the energy selling price, the subsidy, the capital share percentage and the investment cost of the project. This work suggests that the value of the higher subsidy impacts more than the capital share. In a future where energy prices will tend to rise, having fixed incentives may not be beneficial because of the effects of inflation. The fourth implication is the development of renewables must push to strengthen a country's industrial environment, supporting its eventual transformation to produce renewable plants to be installed in the territory.

It is essential to highlight the inherent limitations of this tidal energy study. All results obtained must be considered with the understanding that they are the result of approximations, due to the lack of clarity of the data provided regarding the energy production plant. Incomplete and inaccurate data were supplemented by theoretical deductions, which introduces a significant margin of uncertainty in the final results. Specifically, regarding the plant capacity factor, the only determinant data used was the significant average wave height. However, for a more accurate and representative evaluation of tidal plant performance, it would be useful to consider other crucial parameters as well. These include wave period, wave regularity, wave amplitude, and wave energy distribution. The exclusion of these factors limits the completeness and accuracy of our conclusions about the potential for energy production.

As anticipated, a significant limitation concerns the specifics of the operation of the plant itself. The only indication given is that the plant starts producing energy with waves half a meter high. However, it was not specified how energy production increases as the waves grow. This is a crucial finding, as the plant's response to different wave heights can greatly affect the overall efficiency and energy production capacity. On the other hand, it was pointed out that waves that are too high (more than three meters) are not suitable for the device, but no clear quantitative details on this limitation were provided.

These limitations must be considered to correctly interpret the study results. Future research should aim to collect more complete and accurate data on the plant and consider a broader set of parameters to improve the evaluation of the energy production of tidal power plants. Only through a more detailed and comprehensive approach can an accurate assessment of the potential of this technology for renewable energy production be obtained.

5. Conclusions

The research presented in this work starts from an analysis of marine conditions to calculate the energy production of a hypothetical tidal power plant located on the coast of Livorno. The technical analysis showed that wave height and frequency are crucial variables for energy production. Lower plant efficiency emerges during the months of July and August especially, while there are strong peaks in plant efficiency during the month of February. This determines the first operational implication of this work, which suggests maintenance activity during the summer months to reduce production losses.

The economic analysis shows that the profitability of the 1 MW plant is verified in the base case with a NPV of 573 k€ and a DPBT of 21 years. It is shown that in 75% of the case studies examined the NPV remains positive and the LCOE value is just over 70 €/MWh indicating its competitiveness with other energy sources. Here the second economic implication emerges showing that the realization of these plants is possible in the Italian territory. However, it is worth noting that, if inflation is not included and especially if the selling price of energy is reduced, the respective sensitivity analyses signal an unprofitability that is not clear from the risk analysis. Thus, this project also has unprofitable conditions if a market scenario with an inappropriate energy selling price is applied.

Consequently, the third policy implication emerges. FER2 Decree allows a better economic condition when the subsidy is not constant if market conditions define higher selling prices. This equilibrium point must therefore be carefully monitored. Similarly, the advantages between the capital grant and the value of subsidies depend not only on correction coefficients to be applied to subsidies but also on the investment cost incurred. The NPV varies between 338-1287 k€ in different policy contexts (beyond what is provided by FER2 we evaluated a scenario with only capital grant) and thus is not always greater than the base NPV calculated as a function of an energy selling price of 130 €/MWh subject to inflation over the lifetime. As for the DPBT, on the other hand, it allows an early return on investment and the value falls between 11-15 years. Risk analyses denote an increase of at least ten percentage points in terms of case studies with positive NPV. Finally, it is crucial to emphasize the results of the LCOE. The value close to 49 €/MWh concerns a scarcely real scenario that does not include inflation. The application of a capital grant leads to a reduction of the LCOE, which becomes about 65 €/MWh, but in a cost-plus assumption to realize the investment in a shorter time, the maximum values of the LCOE related to the combined capital grant+subsidies scenario with about 77 €/MWh and in the subsidies scenario with about 90 €/MWh are reached. In this framework, it is crucial to assess the profitability of even small and medium-sized plants and the related socio-economic impacts on local communities and the national industrial supply chain.

From a sustainability perspective, the plant contributes to SDG 7 by improving the efficiency of energy resource use. Although tidal energy in this case shows seasonal variability, it is a valuable addition to the energy mix, offering an alternative energy source that contributes to source diversification and energy system resilience. The ability to predict seasonal variations allows this energy source to be integrated strategically, optimizing energy infrastructure planning and resource management, thereby contributing to the reduction of fossil fuel use and supporting the transition to a sustainable energy system. It also supports SDG 14, as the plant is designed with an approach that emphasizes minimizing ecological impact. In particular, the plant uses technologies that avoid the destruction of essential marine habitats. The structure of the plant is designed to be minimally invasive, relying on existing structures. In addition, the energy infrastructure is designed to be robust and durable, reducing the need for frequent maintenance work that could disturb marine wildlife.

In conclusion, tidal energy supports sustainable development through a green economy-based model that utilizes locally available resources and contributes to the general welfare, however, to be resilient, an appropriate techno-economic analysis that enables policy makers to identify appropriate policies to decarbonize the energy system is essential.

CRediT authorship contribution statement

Matteo Catalano: Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Idiano D'Adamo:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Data curation, Conceptualization. **Massimo Gastaldi:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Marzena Smol:** 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

This study was carried out within the PEACE (Protecting the Environment: Advances in Circular Economy) which received funding from 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 funded by the European Union - Next Generation EU. This manuscript reflects only the authors' views and opinions, and can be considered responsible for them.

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