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Economic Assessment of Ocean Alkalinity Enhancement Through Electrodialysis: The Role of Carbon Credits in Comparing Solar Energy and Thermal Waste Technologies

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ABSTRACT

This study evaluates the economic feasibility of an Ocean Alkalinity Enhancement (OAE) plant for CO_2 removal by comparing Solar Energy (SE) and Thermal Energy Waste (TEW) configurations under varying carbon credit price and inflation scenarios in order to assess investment attractiveness. The methodology is based on a discounted cash flow model, using Net Present Value (NPV) as the primary indicator, applied to a plant with an annual CO_2 removal capacity of 878 tonnes, located in the United States and assessed over a 20-year time horizon. Results show that project profitability is highly sensitive to carbon credit prices. Under high-price scenarios, positive NPVs can be achieved, whereas medium and low-price scenarios consistently result in negative outcomes. Break-even thresholds are estimated at approximately 1177–1472$/t$CO_2$ for the TEW configuration and 1300–1602$/t$CO_2$ for the SE configuration, depending on inflation assumptions and the opportunity cost of capital. The TEW configuration appears more economically robust, exhibiting a higher likelihood of financial viability under favorable market conditions. These findings underline the crucial role of stable carbon markets and supportive policy frameworks in improving the economic sustainability of OAE technologies and fostering circular economy-based business models aligned with marine ecosystem protection, supporting SDG 14.

1 | Introduction

The atmospheric concentration of CO_2 has increased from 280 ppm in pre-industrial times to 419 ppm in 2022 [1]. Climate change and its causes are highly controversial and debated. Whereas the contribution of humankind is undeniable, there are other natural phenomena that are not fully quantified or understood and that contribute mostly to global CO_2 emissions. For instance, processes operating on centennial timescales appear to heavily influence global carbon-cycle dynamics and are still not considered in Earth's models [2]. The atmospheric CO_2 originating from anthropogenic fossil fuels accounted for 23% of total emissions since 1750. It was calculated that the total CO_2 emitted from fossil fuels increased from 0% in 1750% to 12% in 2018, a share that cannot alone justify the cause of global warming [3]. It was also demonstrated that the anthropogenic and natural greenhouse gas emissions (GHGs), for instance volcanoes, are of the same order of magnitude [4].

Advancements in climate technologies, stricter regulations, industrial modernization, and green energy expansion play a key role in reducing carbon emissions, while economic growth and urbanization remain major drivers [5]. Consistently, renewable energy investments and mitigation technologies help limit

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climate risks, although current energy structures and urban expansion continue to exacerbate them [6]. A rebalancing of fiscal measures is needed, with lower taxes on green resources relative to fossil fuels and a progressive reduction of environmentally harmful subsidies [7]. A broader transition toward sustainability, including renewable energy, environmental management, and socio-economic development, is therefore essential [8]. In this framework, stakeholder pressure fosters the adoption of circular economy practices, supporting carbon-neutral supply chains, with net-zero policies and innovation acting as key enablers [9]. Moreover, integrating carbon capture and storage (CCS) within circular economy models allows the valorization of captured CO_2, improving resource efficiency and contributing to sustainability goals [10].

Carbon dioxide removal (CDR) is essential to achieve net zero emissions, but ambitious reduction policies in different sectors can halve the need for it [11]. Climate change requires not only limiting fossil fuel emissions, but also capturing CO_2. Various techniques are used, combining technologies in order to pursue sustainable development [12–14]. Similarly, it is essential to transform waste into resources for a sustainable transition [15, 16]. This is a highly ambitious goal, and there is therefore a need to implement, on an industrial scale and globally, technologies that are already in use in specific cases, such as Direct Air Capture (DAC) [17, 18] and Ocean Alkalinity Enhancement (OAE) [19, 20].

OAE is one of the technological approaches that has the potential to drastically reduce carbon concentrations in the atmosphere, but this technology must be carefully evaluated not only for its technical and economic feasibility, but also for the effects it may have on marine flora and fauna. The project, called the 'Carbon to Sea Initiative', involves several universities and research centers around the world [21].

Other carbon dioxide removal technologies are being actively researched and implemented by several start-ups that have achieved promising preliminary results. The most widely investigated approaches include DAC, in which is absorbed from the air using absorbent solutions or solids, concentrated, stored, and sometimes even used [22, 23], bioenergy with CO_2 capture and storage (BECC), in which particular plants are grown to absorb CO_2, then burned to produce energy and the CO_2emitted is captured, concentrated, stored or utilized [24], and nutrient seeding, in which nutrients are added to the soil to increase carbon sequestration [25].

Research on marine carbon dioxide removal (mCDR) is growing rapidly, although uncertainties remain about individual options [26]. In particular, it includes methods such as OAE, in which alkaline substances or materials are added to the ocean surface to increase its adsorption capacity [27, 28]. OAE has several advantages over other approaches: oceans are the world's largest carbon "sink", covering 71% of the Earth's surface and absorbing around 30% of all CO_2 emissions [29, 30], and the oceans' capacity to absorb CO_2 is several orders of magnitude greater than the amount of CO_2 that needs to be removed.

When CO_2 dissolves in the oceans, carbonic acid (H_2CO_3) is created, thereby decreasing the pH of seawater. In addition to the negative impacts of ocean acidification on the entire biosphere, the shift of this balance toward carbonic acid also inhibits the natural absorption of additional CO_2 [31]. Theoretically, the most efficient way to produce alkaline species is bipolar membrane electrodialysis (BMED). BMED allows the production of diluted sodium hydroxide (NaOH) and diluted hydrochloric acid (HCl) [29]. Several versions of this technology have been developed [32] and improvements have been identified in terms of water dissociation in bipolar membranes [29], the management of membrane fouling and scaling and their durability [33, 34], and the optimisation of plant operating parameters [34]. Some authors propose work related to CO_2 capture technologies [35], and several start-ups and spin-offs have implemented OAE technologies on a pilot scale, including Planeteers (Germany), Limenec (Italy), Planetary (Canada), Vesta Earth (USA) and SeaO2 (Netherlands).

Several recent studies highlight the central role of economic analysis in the development of BMED-based technologies for CO_2 removal and OAE. An analysis based on discounted cash flows shows that the profitability of plants depends heavily on energy, operating and membrane replacement costs, often making it necessary to resort to carbon credits or the valorisation of co-products to support the economic sustainability of the process [34]. Other studies show that laboratory results can be reliably transferred to pilot scale and that techno-economic assessments are essential for estimating minimum production costs and supporting the modelling and optimization of large-scale systems [36]. However, the available analyses focus mainly on individual sub-processes or specific case studies, while there is a lack of integrated economic assessments that systematically capture the entire value chain, revenues from co-products and the role of carbon markets [37, 38]. This highlights a clear gap in the literature regarding the need for comprehensive economic and financial models to assess the real scalability and economic sustainability of BMED solutions for OAE.

The objective of this work is to assess the economic sustainability of a CO_2 capture and utilization plant, comparing Solar Energy and Thermal Energy Waste technological configurations, and to analyze the extent to which carbon credit market conditions and the regulatory framework influence the profitability of the investment and its contribution to environmental sustainability objectives, in particular Sustainable Development Goal (SDG) 14.

2 | Description of the OAE Plant

The OAE plant is based on a BMED system designed to process brine streams produced by a desalination facility. The analysis presented in this study relies on the data reported in [34]. The flow sheet of the plant is shown in Figure 1.

BMED is an electrochemical process that enables the conversion of saline solutions into acidic and alkaline products through the application of a strong electric field generated between two electrodes located at the extremities of a membrane stack. Each membrane unit, referred to as a triplet, consists of a bipolar membrane (BPM), an anion exchange membrane (AEM), and a cation exchange membrane (CEM).

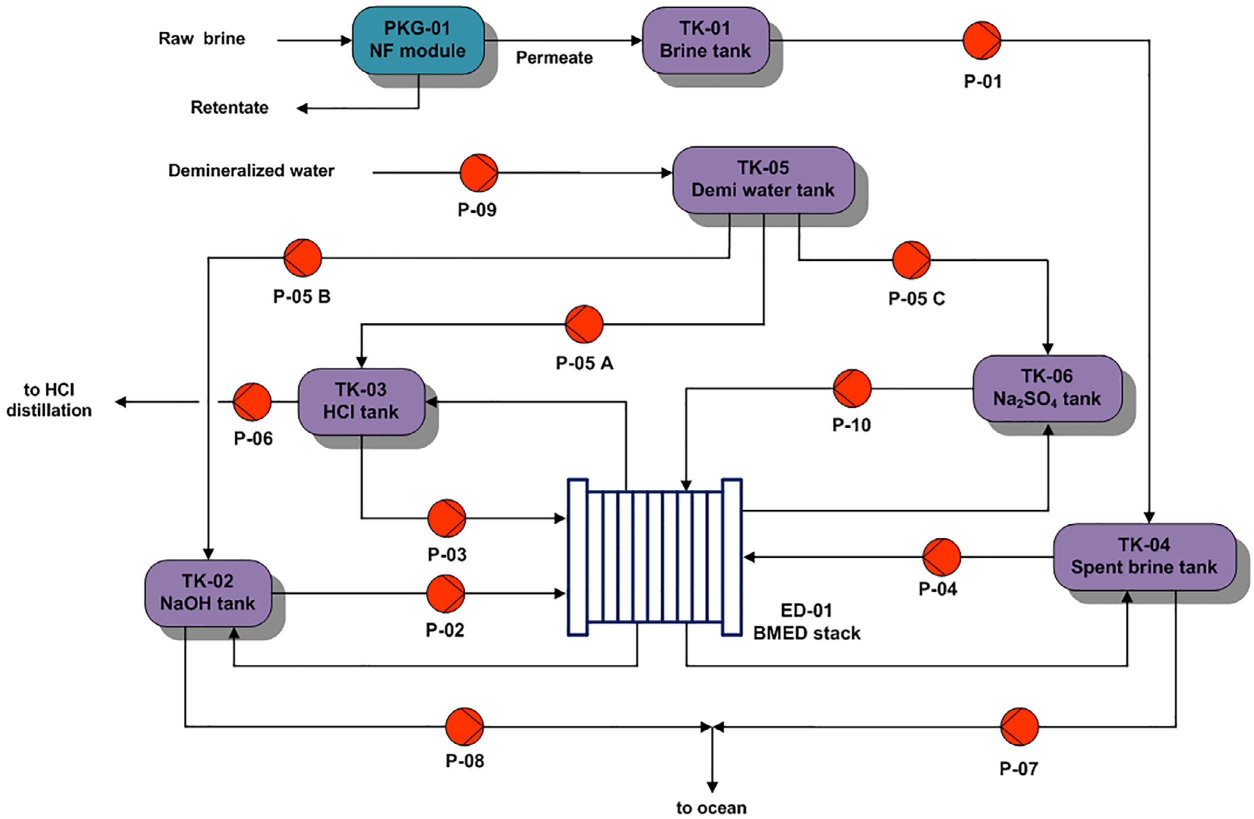

FIGURE 1 | Flow-sheet of the OAE plant based on BMED.

Within each BMED triplet, three isolated compartments are established for acid, base, and salt solutions, which are separated by the BPM, AEM, and CEM. When an external electrical potential is applied, water dissociation occurs at the BPM, generating protons and hydroxide ions. Protons, together with chloride ions migrating from the salt channel, are transported to the acid compartment, where hydrochloric acid (HCl) is formed. Simultaneously, hydroxide ions and sodium ions migrate toward the base compartment, resulting in the production of sodium hydroxide (NaOH). A sodium sulphate (Na_2SO_4) electrolyte, also referred to as the electrode rinse solution (ERS), circulates through the electrode channels to facilitate sodium ion transport across the outer CEMs and to suppress the migration of protons and chloride ions toward the electrodes, where they could otherwise undergo electrochemical conversion to hydrogen (H_2) and chlorine (Cl_2) gases.

The modelled plant operates in a closed-loop (CL) configuration, employing desalination brine as the saline feed. All process streams, including HCl, NaOH, brine, and Na_2SO_4, are continuously recirculated until the target NaOH concentration is achieved. Consequently, the plant is designed to function in batch mode, with its daily production capacity determined by the size of the membrane stack. A typical concentration of brine is 1.3 M of NaCl, which is higher than that of seawater (~0.6 M), which enables the attainment of higher product concentrations. After 3.5 h of operation, the NaOH and HCl streams reach final concentrations of approximately 2.1 and 1.8 wt.%, corresponding to 0.54 and 0.49 mol/L, respectively. The brine discharged from the reverse osmosis (RO) unit of an upstream desalination plant is first subjected to a two-stage nanofiltration (NF) pre-treatment. The NF membranes are employed to reduce calcium and magnesium concentrations below 10 mg/L, a critical threshold for minimizing the risk of mineral scaling on the BPMs, AEMs, and CEMs. Since the OAE plant requires brine or sea water, and the produced NaOH solution, together with the spent solution, is discharged into the sea, the location of the OAE plant shall be along the coast.

The feed brine flow rate is 100 m^3/h while the permeate recovered downstream of the nanofiltration (NF) unit amounts to 70 m^3/h The resulting pre-treated brine is collected in a storage tank whereas the NF retentate stream is conveyed to the outfall and discharged into the marine environment. Operation of the BMED facility requires a supply of deionized water (DIW), which is taken from the permeate stream of the upstream desalination plant. This stream represents a negligible fraction of the total daily water production of a typical desalination facility. In the mechanically agitated tank TK-06, powdered sodium sulphate is dissolved in water to prepare a 200 g/L Na_2SO_4 solution, which serves as the electrode rinse solution (ERS). The use of the ERS mitigates the evolution of hydrogen, oxygen, and chlorine gases in the vicinity of the electrodes, thereby improving overall process efficiency.

The volume ratio of brine to HCl to NaOH was set at 3:1:1 based on experimental trials conducted at a pilot-scale facility in Italy [39]. The HCl distillation package (not reported in the flow-sheet) comprises a storage tank, heat exchanger, distillation column, reboiler, and condenser, all constructed from stainless steel (SS) with a glass lining. The HCl solution is continuously withdrawn from the buffer tank and fed to the distillation column, which operates on a continuous basis concentrating the acid to approximately 20 wt.%, slightly below its azeotropic composition of 20.2 wt.%.

The complete distillation package is assumed to be supplied by a specialized vendor with experience in hydrochloric acid concentration systems and includes a dedicated boiler and chiller for the distillation process. The total duration of a single batch cycle is 4.5 h, comprising 3.5 h of BMED operation, 0.5 h for filling tanks TK-02, TK-03, and TK-04, and 0.5 h for emptying these tanks. Consequently, up to five batch cycles can be completed per day. Assuming 330 operating days per year to account for scheduled shutdowns, holidays, and routine or unplanned maintenance, the plant achieves a daily production capacity of approximately 140 m^3 of NaOH and HCl solutions (28 m^3 per batch over five batches).

The plant's design capacity is 138,600 m^3/y of brine: the total 2.1 wt.% NaOH solution amounts to 47 216 ton/y, whereas the 1.8 wt.% HCl diluted solution is 46 662 ton/y. The spent solution released to the sea, together with NaOH, amounts to the same volume of the incoming brine, as the brine simply increases its salinity at the end of the BMED treatment. Overall, the amount of NaOH released into the ocean can remove around 878 tonnes of CO_2 per year.

3 | Methodology

The Discounted Cash Flow (DCF) method is one of the most established tools for assessing the financial feasibility of a project. The project's revenues come from two main sources. The first component is the generation of carbon credits, associated with the annual amount of carbon dioxide removed from the system. This revenue is a function of the amount of CO_2 sequestered in period t and the unit price of carbon credits expressed per ton of CO_2 removed. The second source of revenue is the sale of hydrochloric acid (HCl), a by-product of the BMED process. The annual amount of HCl generated is determined by the plant's performance, while the associated revenue depends on the unit market price of HCl per ton. The cost structure considered in the economic model includes initial investment costs (CAPEX), including expenses for main equipment, auxiliary systems, engineering and installation, and annual operating costs (OPEX), i.e. costs related to the ordinary operation of the plant, such as labor, raw materials and utilities.

From a CAPEX perspective, membranes account for a significant portion of the cost of the plant's main equipment; similarly, their maintenance and periodic replacement are one of the most critical items among operating costs, as the progressive degradation of membrane performance over time due to phenomena such as fouling and chemical and electrical stress must be taken into account. However, in this paper, we will treat them separately in order to highlight their relevance. This paper starts from the estimates of a previous study [34] and proposes the following model:

$$
\begin{aligned}
NPV = & \sum_{t=1}^{n} \frac{\left[Q_{HCl,t}P_{HCl,t} + Q_{CO2,t}P_{CC,t}\right](1+\inf_r)}{(1+r)^t} - \sum\nolimits_{t=0}^{nd} \frac{\left(\frac{Cinv}{nd}\right) + (Cinv - CIcs,t)\,rd}{(1+r)^t} \\
& - \sum_{t=0}^{n} \frac{\left[C_{ME,t} + C_{UE,t} + C_{AU,t} + C_{IT,t} + C_{T,t} + C_{YC,t} + C_{LE,t} + C_{I,t} + C_{P,t} + C_{ID,t} + C_{I,t} + C_{E,t} + C_{B,t} + C_{LP,t}\right](1+\inf)^t}{(1+r)^t} \\
& - \sum_{t=1}^{n} \frac{\left[C_{EPC,t} + C_{ST,t} + C_{C,t} + C_{RM,t} + C_{L,t} + C_{LQR,t} + C_{CO,t} + C_{WT,t} + C_{U,t} + C_{M,t} + C_{MA,t} + C_{SU,t}\right](1+\inf)^t}{(1+r)^t}
\end{aligned} \quad (1)
$$

Several indicators are proposed, such as Net Present Value (NPV), which quantifies the project's profits; Discounted Payback Time (DPBT), which measures the period required to recover the initial investment; Profitability Index (PI), which indicates the value created for each euro invested; and Internal Rate of Return (IRR), which represents the percentage return generated by the project. These indicators are used in various fields to assess the sustainability of projects [40, 41] and CO_2 recovery processes [42, 43]. In addition, the Levelized Cost of CO_2 Removal (LCOD) is also proposed, which represents the average cost per ton of CO_2 removed over the entire lifecycle of a technology. It is calculated as the ratio of the sum of discounted costs (CAPEX, OPEX, etc.) to the sum of CO_2 removed, which is also discounted over time [44, 45].

The study and operation of bipolar membrane electrodialysis (BMED) is based on a plant with a removal capacity of 878 tonnes of CO_2 per year. Two case studies are examined:

- the technological context that uses solar energy (SE) and;
- the technological context using waste thermal energy from neighbouring plants (TEW).

where $Q_{HCl,t}$ = quantity of HCl produced in period t in tonnes; $Q_{CO2,t}$ = quantity of CO_2 removed in period t in tonnes; $P_{HCl,t}$ = unit price of HCl per tonne; $P_{CC,t}$ = unit price of carbon credits per tonne of CO_2 removed; $C_{ME,t}$ = purchase cost of Main Equipment; $C_{UE,t}$ = purchase cost of Utilities Equipment; $C_{AU,t}$ = purchase cost of Auxiliary and Unlisted equipment; $C_{IT,t}$ = Import Tariffs cost; $C_{T,t}$ = Transportation cost; $C_{YC,t}$ = Yard cost Improvement and Civil works; $C_{LE,t}$ = cost of Laboratory Equipment; $C_{I,t}$ = cost of Installation; $C_{P,t}$ = cost of Piping; $C_{ID,t}$ = cost of Instrumentation and Distribution control system; $C_{I,t}$ = cost of Insulation; $C_{E,t}$ = cost of Electrical equipment; $C_{B,t}$ = cost of Buildings; $C_{LP,t}$ = cost of Land Purchase; $C_{EPC,t}$ = Engineering, Procurement and Construction cost; $C_{ST,t}$ = Supervision and Training cost; $C_{C,t}$ = Contingencies cost; $C_{RM,t}$ = Raw Materials cost; $C_{L,t}$ = Labour cost; $C_{LQR,t}$ = Laboratory, Quality Control and R&D cost; $C_{CO,t}$ = Consumables cost; $C_{WT,t}$ = Waste Treatment cost; $C_{U,t}$ = Utilities cost; $C_{M,t}$ = Miscellaneous cost; $C_{MA,t}$ = Maintenance cost; $C_{SU,t}$ = Start-up cost; C_{inv} = invested capital; $C_{Ics,t}$ = loan amount repaid at time t; r_d = interest rate on the loan; r = opportunity cost of capital; n_d = loan term; n = useful life of the project; inf = inflation rate; $\inf_r$ = inflation rate on revenues with t = cash flow period, $t \in [0,20]$.

TABLE 1 | CAPEX for the two technological contexts.

Cost items	SE context ($)	TEW context ($)
Main equipment	3 466 138	3 466 138
Utilities equipment	848 908	253 908
Auxiliary and unlisted equipment	86 300	74 400
Equipment purchase cost	4 401 347	3 794 446
Import tariffs (if any)	26 839	26 839
Transport	171 546	171 546
Yard improvement + civil works	188 735	188 735
Laboratory equipment	50 000	50 000
Installation	660 202	569 167
Piping	177 642	177 642
Instrumentation + DCS	396 121	341 500
Insulation	22 006	18 972
Electricals	132 040	113 833
Buildings	264 080	227 667
Land purchase (38$/m2)	186 200	186 200
Total plant direct cost	6 676 760	5 866 549
Engineering, procurement, construction	467 373	410 658
Supervision, start-up & training	267 070	234 661
Contingencies	33 384	29 332
Total plant indirect cost	767 827	674 653
Direct fixed capital	7 444 587	6 541 201

TABLE 2 | OPEX for the two technological contexts.

Cost items	SE context ($)	TEW context ($)
Raw materials	139 708	139 708
Labour (plant manager, 3 workers)	228 000	228 000
Transport	0	0
Laboratory/QC/R&D	10 000	10 000
Consumables	15 000	15 000
Waste treatment/disposal	5000	5000
Utilities (electricity)	175 244	139 879
Miscellaneous (marketing, administrative costs)	7000	7000
Technical operating cost	579 952	544 587

TABLE 3 | Maintenance costs.

Cost items	$
BMED stack ED-01 (membrane only)	1 212 825
Maintenance & repairs	9702
Insurance and local taxes	4851
Total maintenance	1 227 379

TABLE 4 | Revenue.

Revenue items	Pi ($/t)	Qi (t)
HCl	100	4034
Low CO_2	476	878
Medium CO_2	813	878
High CO_2	1515	878

Given the absence of reference values in the literature, the input data are chosen in accordance with a previous analysis [34] involving a number of international industry experts who provided their recommendations on the values chosen. The idea of choosing a conservative approach emerged. The plant is installed in the United States, its useful life is assumed to be 20 years and the opportunity cost of capital is set at 5%. Inflation is modelled using different values: a rate of 2.5% is applied to cost items, while two alternative scenarios are considered for revenues, equal to 0% and 2% respectively, depending on the market scenario analyzed. This approach is intended to give greater weight to cost developments than to potential revenue increases, in line with a conservative approach.

The sum of Total Plant Direct Costs and Total Plant Indirect Costs determines Direct Fixed Capital (CAPEX), which in the SE technological context is equal to 7 444 587$, while in the TEW technological context it is equal to 6 541 201$ (Table 1). The percentage estimates and items are calculated using the same method in both case studies, but the costs in the first case are higher because, as waste substances from neighboring plants are not used, it is necessary to add equipment to the main plant in order to concentrate the HCl obtained from the process, which is therefore more expensive.

Following the investment costs, the annual operating costs (OPEX) were estimated, which include all expenses necessary for the operation of the plant on an annual basis (Table 2). The transport of HCl is borne by the purchaser and is therefore assumed to be zero. Specifically, the costs associated with the maintenance of the membranes, which need to be replaced every three years, are proposed for both contexts (Table 3).

As previously explained, the revenues associated with the process analyzed derive from two main sources (Table 4): the generation of carbon credits linked to the annual amount of CO_2 removed and the direct sale of 20% concentrated HCl as a by-product of the process. The annual amounts of CO_2 removed and HCl obtained are derived from technical analysis. The high variability of carbon credit prices makes it necessary to consider different reference

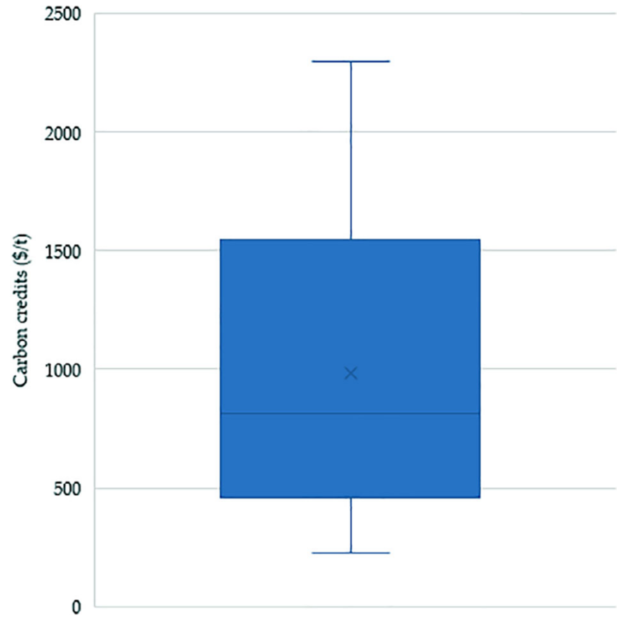

FIGURE 2 | Distribution of carbon credit prices ($/t).

scenarios in order to capture the intrinsic uncertainty of this market.

To estimate the value of carbon credits associated with CO_2 removal, a database made public by the Frontier initiative [46] was used. This initiative funds projects characterized by technologies similar to those covered in this study, thus making the comparison meaningful. Credit prices were estimated by referring to the percentiles in the database (Figure 2). The first percentile was taken as the Low scenario, the second percentile as the Medium scenario, with a value similar to the sample average, and the third percentile as the High scenario. Finally, a scenario with revenue inflation (Inf at 2%) and without inflation (Ninf therefore at 0%) was considered.

4 | Results

4.1 | Base scenario

The estimated LCOD values are 1788$/tCO_2$ removed for the SE-based configuration and 1662$/tCO_2$ removed for the TEW configuration. These results reflect only the economic component of the system but nevertheless provide a useful indication for comparing the different technological options, highlighting the relative cost-effectiveness of the TEW solution in the case analyzed. It should be noted, however, that a comprehensive performance assessment requires the integration of additional analytical dimensions, including life-cycle environmental impacts, scalability potential, and any systemic benefits associated with the different configurations.

The base scenario considers CAPEX, OPEX and membrane maintenance costs, as well as revenues associated with carbon credits and the direct sale of concentrated HCl. A plant with a removal capacity of 878 tons of CO_2 per year and a time horizon of twenty years is analyzed.

TABLE 5 | Profitability analysis—Solar Energy configuration.

Case study	Description	NPV ($)
1	High+Inf	2 081 571
2	High+Ninf	−751 494
3	Med+Inf	−5 507 780
4	Med+Ninf	−7 568 814
5	Low+Inf	−9 394 477
6	Low+Ninf	−10 939 305

TABLE 6 | Profitability analysis—Thermal Energy Waste configuration.

Case study	Description	NPV ($)
7	High+Inf	3 270 416
8	High+Ninf	$458 904
9	Med+Inf	−4 072 373
10	Med+Ninf	−6 133 407
11	Low+Inf	−7 959 070
12	Low+Ninf	−9 188 071

Twelve basic case studies are proposed, derived from the combination of two plant configurations (Table 5 and Table 6), namely SE and TEW, three carbon credit prices (Low, Med and High) and the presence or absence of inflation applied to revenues (Inf and Ninf).

In the SE configuration, only case study 1, characterized by the most favorable market conditions, is economically profitable, with an NPV exceeding $2 million. It can also be seen that the difference between the various case studies in terms of inflation tends to decrease as market conditions worsen: in particular, the difference in NPV between case study 1 and case study 2 is 2 833 065$, while between case study 5 and case study 6 it is reduced to 1 544 828$. These differences depend on the effect of inflation, which is more pronounced in market contexts where the price of carbon credits is higher.

In the TEW technological configuration, two case studies are economically profitable, in particular case study 7, with a NPV exceeding 3 million $, and case study 8, with a NPV just under 500 000$. These results highlight how the savings derived from lower initial investment costs, together with the circular economy benefits generated by the use of waste streams from neighboring plants, play a crucial role in the overall profitability of the project. Overall, each case study relating to the TEW configuration is more cost-effective than the corresponding market scenario for the SE configuration. Analysis of the tables also shows that, in both configurations considered, the common condition for economically profitable case studies is the adoption of the high level of carbon credit prices.

In order to examine the composition of the economic results in greater detail, the following figure shows the percentage

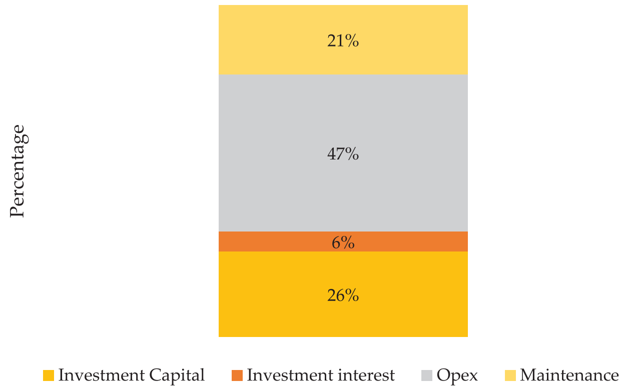

FIGURE 3 | Cost distribution.

distribution of the main cost items over the entire useful life of the plant, taking case study 2 (high price, no inflation on revenues) as a reference. The analysis shows that the predominant component is annual operating costs, which account for approximately 47% of the total. However, it should be noted that the maintenance item, equal to 21%, includes only the cost associated with replacing the membranes, which differs from annual operating costs in that it is not recurring on an annual basis (Figure 3). With regard to opex, labor stands out (39%), followed by utilities (30%) and raw materials (24%) – Figure 4.

As regards revenue items, their percentage incidence varies according to the market scenario considered, as one of the determining components is carbon credits. The following table shows how the percentage distribution of revenues changes as the different market scenarios analyzed vary in the absence of inflation. In fact, carbon credits cover three-quarters of revenues in the High scenario and half in the Low scenario (Figure 5).

In addition to the NPV, other indicators were evaluated in order to complete the assessment of the plant's economic feasibility. Due to extraordinary maintenance operations, additional costs are generated, which cause numerous variations in cash flows over the useful life of the project. Consequently, due to one of the IRR traps, this indicator cannot be calculated. The DPBT is >20 y in all non-profitable contexts. This indicator varies from 13 to 19 years in case studies 7 and 8 respectively, showing the impact of inflation on revenues. However, it is 15 years in case study 1. The PI ranges from 1.06 to 1.46 in case studies 7 and 8, confirming what was previously mentioned. Finally, the PI generates 1.26$ for every $ invested in case study 1.

4.2 | Sensitivity Analysis

A sensitivity analysis was conducted to assess the economic robustness of the model and understand the impact of the main variables on the final result. The selection of critical variables for analysis was guided exclusively by previously obtained data. As shown by the distribution of revenues, the only two items that emerge are carbon credits and the direct sale of HCl. On the cost side, the cost of replacing membranes and, among opex, the cost of labor emerges. In addition, a fundamental variable in cash flows, such as the opportunity cost of capital, is included.

The study is limited to the TEW technological context, which emerged as preferable to the SE context, and the two case studies with the highest and lowest profitability are analyzed, namely case study 7 (High+Inf) and case study 12 (Low+Ninf). The presence of two initial case studies and the five variables modified in a pessimistic and optimistic context leads to the development of 20 new case studies (Table 7 and Table 8).

The sensitivity analysis shows that the NPV is particularly influenced by the opportunity cost of capital (between 18%–21%) and the price of carbon credits (between 22%–27%), which generate the highest percentage changes. In particular, an increase in the discount rate or a reduction in the price of carbon credits leads to a significant decrease in the net present value. Conversely, changes in labor and maintenance costs have a more limited effect on the net present value, indicating that the project is less sensitive to these cost items. The lower percentage delta is associated with the price linked to the sale of HCl.

Even in this scenario, the project shows greater sensitivity to changes in the opportunity cost of capital. The changes are more modest (5%), but this also depends on the starting numerical value, which is significantly larger in absolute terms. This time, labor and manpower costs have a greater percentage impact than revenues from carbon credits. However, despite the parameter adjustments, the NPV remains negative in all cases, indicating that the variations considered are not sufficient to make the project economically sustainable.

4.3 | Break-Even Analysis

The break-even point analysis was conducted for both technological configurations (SE and TEW) in order to identify the price of carbon credits and the replacement cost of the membrane s. With regard to the first variable, it is considered to be evaluated in both configurations with or without inflation on revenues. Furthermore, the analyses are also evaluated for a different opportunity cost of capital equal to 6%, instead of the reference value of 5%, in order to assess the impact of this economic parameter on the results of the model. This choice is motivated by the results of the sensitivity analysis (Table 9).

The values identified represent the critical thresholds beyond which the NPV becomes zero and the investment is no longer economically viable. The results obtained using a discount rate of 5% show that, out of four estimated values, three are lower than the reference price of the high market scenario (1515$/t$CO_2$), while one, relating to the SE configuration in the absence of inflation on revenues, is higher. This finding is consistent with the results of previous analyses, in which case study 2 was the only high scenario characterized by a negative economic result. The increase in the opportunity cost of capital does not lead to a significant increase in the break-even price of carbon credits, which rises only slightly, with maximum variations of around 3% compared to the initial value.

Subsequently, attention was turned to the maintenance cost of the membranes. In this case, the analysis was extended to consider all twelve basic case studies. However, it was only possible to identify

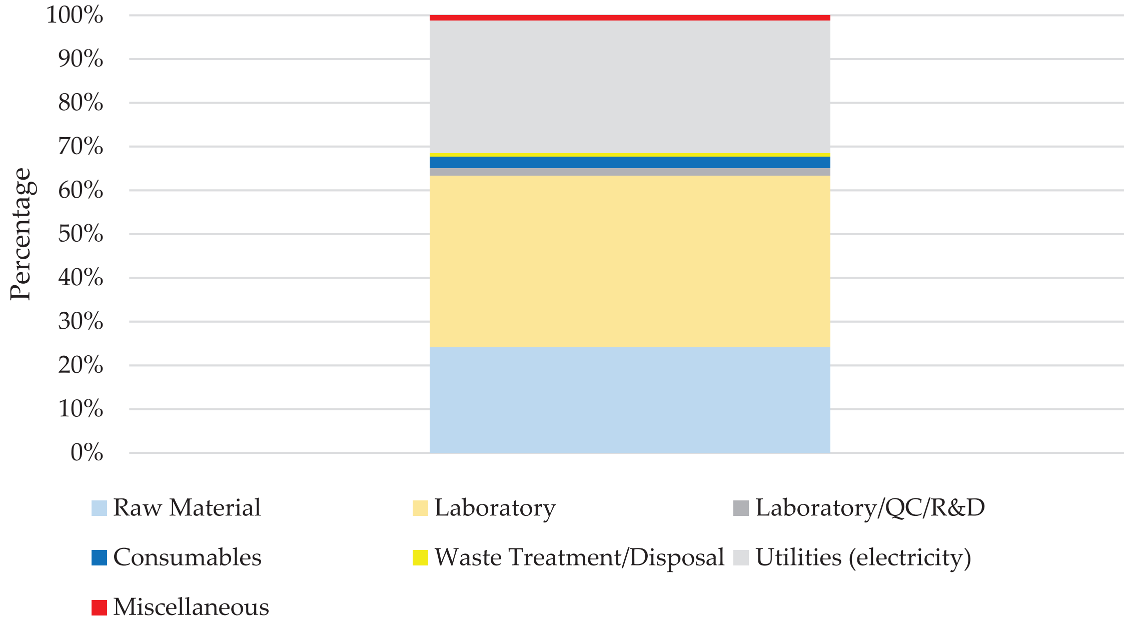

FIGURE 4 | Distribution of opex.

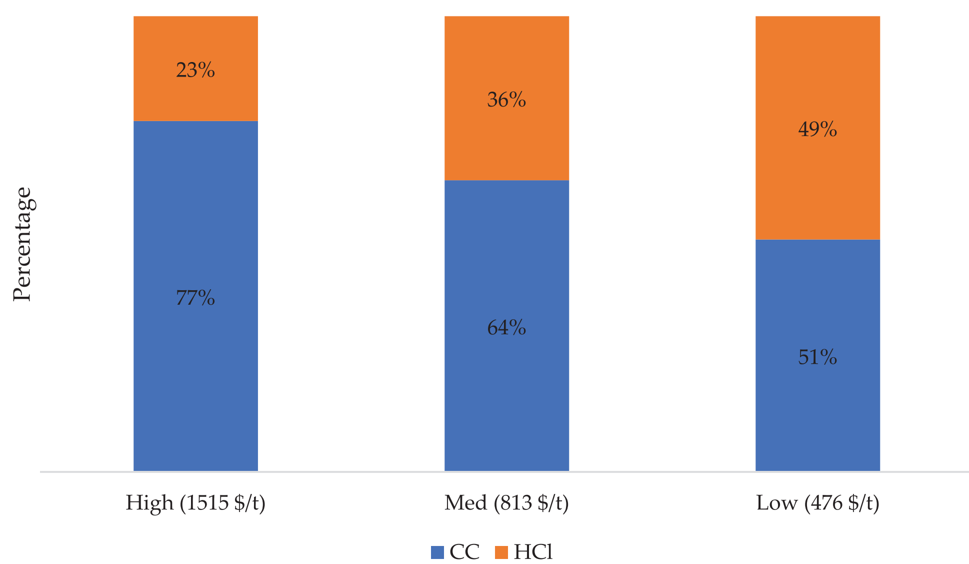

FIGURE 5 | Revenue distribution.

a positive value for the replacement cost of the membranes compatible with a zero NPV in case studies characterized by a high market scenario. In the other case studies, in fact, the break-even value associated with the cost of membrane s was reduced to unrealistic levels, assuming negative values, a circumstance that renders the break-even analysis meaningless for these case studies. It is therefore also logical that case study 2 (unprofitable in the base case) requires a cost lower than the base value (Table 10).

This result highlights how, at the current stage of technological development, a reduction in membrane maintenance costs, while contributing to an improvement in overall profitability, is not in itself sufficient to guarantee the economic sustainability of the project. The break-even analysis therefore highlights that economic sustainability is heavily dependent on favorable market conditions.

4.4 | Risk Analysis

In order to assess the variability of the overall economic result, a Monte Carlo analysis was conducted based on 1000 iterations for each of the base case studies considered. The analysis involved the simultaneous variation of the two variables identified as most critical, namely the price of carbon credits and the cost of membrane maintenance. The average value is assumed to be equal to the starting value and the standard deviation is based on what was proposed in the sensitivity analysis. Again, the analyses are replicated for a different opportunity cost of capital (Table 11).

TABLE 7 | Sensitivity analysis of the TEW context—High+Inf case study.

Variable	Case study	Initial value	Final value	New NPV ($)	Δ Percentage	Base NPV ($)
Opportunity cost capital	13	5	6	2 686 268	−18	3 270 416
Opportunity cost capital	14	5	4	3 955 344	21	
HCl price	15	100	105	3 492 863	7	
HCl price	16	100	95	3 178 986	−3	
CC price	17	1515	1590	4 169 333	27	
CC price	18	1515	1439	2 536 844	−22	
Maintenance	19	1 212 825	1 334 108	2 903 439	−11	
Maintenance	20	1 212 825	1 091 543	3 637 392	11	
Labour cost	21	$228 000	262 200	2 848 969	−13	
Labour cost	22	$228 000	$193 800	3 691 862	13	

TABLE 8 | Sensitivity analysis of the TEW context—High+Inf case study.

Variable	Case study	Initial value	Final value	New NPV ($)	Δ Percentage	Base NPV ($)
Opportunity cost capital	23	5	6	−8 729 847	−5	−9 188 071
Opportunity cost capital	24	5	4	−9 692 311	5	
HCl price	25	100	105	−8 960 187	−2	
HCl price	26	100	95	−9 415 955	2	
CC price	27	476	500	−8 951 886	−3	
CC price	28	476	452	−9 424 256	3	
Maintenance	29	1 212 825	1 334 108	−9 598 658	4	
Maintenance	30	1 212 825	1 091 543	−8 777 484	−4	
Labor cost	31	$228 000	$262 200	−9 675 290	5	
Labor cost	32	228 000	193 800	−8 703 900	−5	

TABLE 9 | BEP—Price of carbon credits.

Technological configuration	Inflation	Final Value (r = 5%)	Final Value (r = 6%)	Percentage delta
SE	2	1300$/t	1339$/t	+3
SE	0	1602$/t	1634$/t	+1.9%
TEW	2	1177$/t	1212$/t	+2.9%
TEW	0	1472$/t	1490$/t	+1.2%

The results of the twelve Monte Carlo simulations show marked heterogeneity in the probability of achieving a positive return on investment. In particular, in the four case studies characterized by high market scenarios, there are different probabilities of obtaining a positive NPV, reflecting the sensitivity of the project to more favorable market conditions. Conversely, for the remaining eight case studies, the probability of obtaining a positive economic return is zero, confirming what has already emerged from previous analyses. The results show that the increase in the opportunity cost of capital does not significantly affect the probability of obtaining a positive economic return in high market scenarios characterized by inflation on revenues.

TABLE 10 | BEP—Membrane maintenance cost.

Case study	Final value ($)	Base value ($)
1	1 900 766	1 212 825
2	990 843	
7	2 293 669	
8	1 348 380	

TABLE 11 | Risk analysis—Probability NPV > 0.

Case study	p(NPV) > 0 (r = 5%)	p(NPV) > 0 (r = 6%)
1	99.4	97.8
2	17.4	9.2
3	0	0
4	0	0
5	0	0
6	0	0
7	99.9	99.8
8	72.5	58.2
9	0	0
10	0	0
11	0	0
12	0	0

5 | Discussion

The results of this study fit into the broader framework of literature on CDR technologies, particularly OAE based on electrochemical systems such as BMED. Several studies highlight how the economic sustainability of such solutions is strongly influenced by energy costs, membrane durability and the valorization of chemical co-products [34, 47, 48]. The economic results obtained in this work confirm this approach, showing that profitability can only be achieved in scenarios characterized by high carbon credit prices and plant configurations capable of minimizing energy costs.

The comparison between SE and TEW configurations confirms the decisive role of energy integration and the circular economy in environmental electrochemical processes. In particular, some analyses [29, 49] emphasize that the use of waste heat or electricity flows can significantly reduce the levelized cost of CO_2 removal, improving competitiveness compared to other CDR technologies such as DAC or Bioenergy with Carbon Capture and Storage (BECCS). The higher profitability observed in TEW scenarios is consistent with this evidence, while maintaining a strong structural dependence on revenues from voluntary or regulated carbon markets.

Some works underlined the role of techno-economic analysis within CO_2 utilization and removal [50, 51]. CO_2 reduction can be achieved within the framework of the 3Es (energy efficiency, renewable energy and circular economy). Some analyses show that it is essential to estimate their price. For example, the European Union allowance fluctuates between 78 and 91€/tCO_2 [52]. China's Emission Trading System (ETS) effectively mitigates emissions in pilot regions and industries, particularly production-based emissions, but can cause carbon leakage to non-pilot areas. Its experience offers valuable lessons for other emerging economies [53]. A sensitivity analysis conducted in USA suggests that the price of oil, economic growth, and carbon price are the three most significant factors in affecting the fleet-level carbon emissions [54]. In this study, sensitivity analysis highlights a marked exposure of NPV to changes in the price of carbon credits and the opportunity cost of capital, which highlight the high uncertainty and volatility of carbon markets for CDR projects over long time horizons. Conversely, labor and membrane maintenance costs, although significant in absolute terms, have a marginal impact on percentage changes in NPV, suggesting that macroeconomic and regulatory drivers dominate overall financial performance.

The break-even analysis and Monte Carlo simulation further reinforce the interpretation that, at the current stage of technological development and market maturity, BMED-based OAE remains heavily dependent on high and stable price signals for carbon credits. This result identifies the need for public policies, support mechanisms and clear regulatory frameworks to facilitate the transition of CDR technologies from the pilot phase to industrial-scale deployment [55–57].

The cost of CO_2 removal using OAE technologies currently varies significantly, both due to different technological approaches and the management of by-products. Recent studies estimate that the levelized cost of removing CO_2 from the atmosphere using acid-base recycling processes ranges from 500 to 800$/t$CO_2$, with carbon efficiencies between 41% and 72%, while without recycling, costs exceed 3000$/t$CO_2$ [37]. An assessment of the logistics chain for the production, transport and distribution of $Ca(OH)_2$ estimated abatement costs of 306–331 USD/tCO_2, with extraction, processing and transport costs dominating the overall economy [58]. Break-even analysis of OAE plants powered by renewable energy shows carbon credit costs between 2666 and 3133$/t$CO_2$, varying depending on the energy source (wind or combined with tidal) [38].

In terms of market and profitability, some analysis estimated that, considering the sale of HCl by-products, the levelized cost per ton of CO_2 removed varies between 848 and 1076 USD/tCO_2. However, to make the project attractive to investors with modest returns, carbon credits would need to be sold between 1395 and 1805 USD/tCO_2, values already comparable to some current prices in the voluntary carbon credit market [34]. The EDBM unit analysis also shows that, on a semi-industrial scale, the minimum cost of NaOH production is around 278€/t, confirming that economies of scale can significantly influence economic performance [36]. By comparison, similar technologies such as low-temperature DAC with solid sorbents, powered by hybrid PV-Wind-battery systems in Moroccan conditions, have shown CO_2 capture costs estimated between 60 and 222€/tCO_2, depending on the time scenario and the use of residual heat [59].

In this context, a more detailed comparison of the main technological options available in the literature helps to better frame the economic positioning and operational constraints of OAE systems. Different OAE strategies exhibit heterogeneous costs and criticalities along the CO_2 removal value chain. Conventional ocean liming, based on limestone calcination to produce CaO or $Ca(OH)_2$, shows cost estimates of 72–159 US$/t$CO_2$, but is penalized by the high energy demand of the calcination phase and the associated process emissions, making the net carbon balance strongly dependent on the energy source and the potential integration of CO_2 capture and storage [60]. More recent assessments report values of 130–295$/t$CO_2$ net removed, highlighting how real performance depends on operational conditions such as CO_2 absorption efficiency, alkalinity dispersion, and the risk of carbonate precipitation [61]. Logistic variants introduce additional complexity. The aerial dispersion of $Ca(OH)_2$ presents highly variable costs (30–1846€/tCO_2, excluding lime costs), and appears less competitive than maritime transport due to higher operational and energy requirements, despite offering greater spatial coverage [62]. Integrated systems combining biomass conversion, hydrogen production, ocean liming, and CO_2 storage show lower costs (98$/t$CO_2$, reducible to 64$/tCO_2 when accounting for energy revenues), but require complex infrastructure, sustainable biomass supply, and advanced CCS integration [63]. Alternative approaches such as buffered accelerated weathering of limestone (BAWL) report intermediate costs (142–189€/tCO_2), but are closer to ocean-based carbon storage systems than direct atmospheric removal, as they rely on concentrated CO_2 streams, reactors, and dedicated infrastructures [64]. At larger scales, OAE has been estimated to potentially reach 100–130$/t$CO_2$, leveraging the ocean as both a capture and storage medium, thereby reducing capital and energy requirements [65].

Overall, compared to BMED-based systems, these approaches shift the economic bottleneck to different stages of the process, including reagent production, logistics, process integration, or the handling of concentrated CO_2 streams. Therefore, comparisons based solely on cost per ton are insufficient, and a comprehensive assessment should also account for energy demand, scalability, indirect emissions, and potential impacts on marine ecosystems.

From an environmental perspective, OAE presents both potential benefits and uncertainties that should be explicitly considered alongside economic performance. On the one hand, increasing seawater alkalinity can enhance the ocean's capacity to absorb atmospheric CO_2 and mitigate acidification, generating positive externalities for marine ecosystems [29, 30, 66]. On the other hand, localized alterations in seawater chemistry – particularly pH shifts and changes in carbonate equilibria, may produce unintended impacts on marine biodiversity—especially in sensitive coastal environments [19, 27]. These aspects highlight the need for integrated assessment frameworks that combine techno-economic analysis with environmental evaluation tools, such as life cycle assessment and monitoring, reporting, and verification systems [44, 55, 67]. In this context, the environmental sustainability of OAE cannot be assumed a priori, but should instead be evaluated in relation to site-specific conditions, scale of deployment, and long-term ecosystem responses.

OAE is closely linked to SDG 14, particularly Target 14.3 on reducing ocean acidification, and has the potential to contribute to both climate mitigation and the protection of marine ecosystems. However, its effects on biodiversity and fisheries remain uncertain and highly dependent on socioeconomic contexts: sustainable scenarios foster synergies between OAE and marine resource management, while high-emission contexts amplify trade-offs [20, 68]. In this context, achieving the goals of SDG 14 requires integrated systems for monitoring ecosystem responses, for example through advanced biodiversity tracking techniques useful for supporting fisheries management and conservation [69]. A systemic and place-based approach, linking coastal pH dynamics to other Sustainable Development Goals, is therefore essential to avoid trade-offs and maximize co-benefits between climate mitigation and marine ecosystem resilience [70].

Despite the growing body of technical and partial analyses, there remains a lack of systematic studies that comprehensively evaluate the economic performance of OAE across the entire value chain, including carbon market variability and energy integration. This gap limits the robust assessment of the long-term economic sustainability of these technologies at an industrial scale.

6 | Conclusion

The financial analysis conducted on the two technological assets, Solar Energy and Thermal Energy Waste, highlights how the economic sustainability of solutions for CO_2 capture and utilization is strongly dependent on market conditions and the regulatory framework. In particular, the results show that only in scenarios characterized by high carbon credit prices and, to a lesser extent, the application of inflation to revenues, does the project manage to generate a positive NPV and therefore prove attractive to private investors. This evidence is of central importance in linking economic performance and environmental sustainability objectives, particularly with regard to SDG 14.

The possibility of removing 878 tons of CO_2 annually is not only a climate benefit, but also an indirect action to protect marine biodiversity and water quality. However, the results show that this environmental benefit, although significant in terms of systemic impact, is not in itself sufficient to guarantee the economic sustainability of the investment. This results in a structural tension between environmental value and financial value, which can only be bridged through market and policy mechanisms that can more effectively internalize the positive externalities generated by the project.

From a managerial point of view, sensitivity and risk analysis provides clear indications of the priority strategic levers. The price of carbon credits and the opportunity cost of capital emerge as the variables with the greatest impact on NPV, especially in high-profitability scenarios. This implies that investment decisions should be strongly oriented toward financial and market risk management, for example through long-term contracts for the sale of carbon credits or hedging instruments against price volatility. At the same time, the systematic preference for the TEW configuration over the SE configuration suggests the importance of business models based on the circular economy and the valorization of industrial waste streams. Integration with existing plants reduces initial investment costs and improves the economic resilience of the project, making it less exposed to fluctuations in environmental revenues. The managerial implications also extend to the structure of operating costs. Although membrane maintenance and labor are less sensitive than carbon credits, they represent a significant share of total costs over the entire life cycle of the plant. This highlights the need for strategies focused on technological innovation in membranes, standardization of maintenance processes and staff training, in order to limit the impact of these items in the medium to long term. From this perspective, collaboration with technology suppliers and research centers can be a key competitive factor in improving operational efficiency and strengthening the economic sustainability of the project.

In terms of public policy, the results highlight the crucial role of the regulatory framework in making solutions that generate environmental benefits in line with SDG 14 economically viable. The high dependence of NPV on the price of carbon credits shows that stable, transparent carbon markets with price signals consistent with climate objectives are essential for attracting private capital to CO_2 capture technologies. In the absence of such conditions, there is a risk that projects with high environmental value will remain confined to an experimental or heavily subsidized dimension. In this context, policy instruments such as tax incentives, minimum price guarantee mechanisms for carbon credits, but also subsidized financing schemes or capital cost guarantee funds can play a decisive role in reducing the risk perceived by investors. Such measures would not only promote the spread of economically sustainable plants, but would also help to strengthen the link between climate policies and the protection of marine ecosystems, creating a direct synergy between SDGs 13–14.

The study has some limitations. The first concerns the simplifying assumptions about the behavior of variables, which do not fully capture market volatility. It is also necessary to assess the impact of different policies and different plant locations. Finally, in order to provide a complete picture of sustainability, both environmental and social contributions are required. At the same time, the technological side can be assessed through learning effects but also by including technological innovation.

In conclusion, the study highlights how economic and environmental sustainability cannot be considered separate dimensions. The implementation of projects that can make a concrete contribution to the protection of oceans and marine ecosystems requires an alignment between management choices geared toward efficiency and industrial integration and public policies capable of economically enhancing the environmental benefits generated. Only through this integrated approach will it be possible to transform the contribution to SDG 14 from an ethical and environmental goal to a real economic opportunity for the industrial and financial sectors.

Author Contributions

All authors (Idiano D'Adamo, Gabriele Graziano, Francesco Ferella) have the same contributions.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available in the supplementary material of this article.

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