Journal of CO2 Utilization 68 (2023) 102375

Contents lists available at ScienceDirect

Journal of CO2 Utilization

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

# Selection of a $CO_2$ capture technology for the cement industry: An integrated TEA and LCA methodological framework

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ARTICLE INFO

*Keywords:*
Cement
CCUS
LCA
Oxyfuel
Post-combustion
CaL
TEA

ABSTRACT

The cement industry generates 7 % of global anthropogenic $CO_2$ emissions, and carbon capture, utilization and storage is one of the most promising technologies to decarbonise the cement manufacturing process. However, it requires specific in-depth techno-economic and environmental analysis to explore different pathways for its implementation in distinct contexts. This paper develops a methodological framework that responds to this challenge, which includes a multi-criteria assessment (with environmental, technical, and economic considerations), and demonstrates its use in a case study to select the most viable $CO_2$ capture technology to be implemented in a Portuguese cement plant. Three technologies were analysed: monoethanolamine (MEA), calcium looping (CaL) post-combustion, and oxyfuel. A reference cement plant without $CO_2$ capture was studied to establish a baseline. The systematic analysis of these technologies' implementation to the cement plant, combined a life cycle assessment and techno-economic assessment, which were integrated with an analytic hierarchy process, and a weighted sum model, reflecting the inputs from the stakeholders. Three scenarios that reflect the feasibility of the $CO_2$ capture unit implementation (worst, intermediate, and best-case) were compared for each of the alternatives. The results show that, regardless of the scenario, CaL has the highest rank among the three $CO_2$ capture technologies. Still, the rank order regarding the reference cement plant depends on the scenario adopted. In the worst scenario, the reference plant presents the highest overall rank, while for the remaining scenarios, CaL has the highest score. In the best scenario, all the technologies present a higher ranking compared to the reference.

## 1. Introduction

Cement manufacturing is responsible for around 7 % of total anthropogenic $CO_2$ emissions [1–3]. About 60 % of the $CO_2$ generated is an intrinsic part of the process, due to the calcination of limestone, while the remaining 40 % is due to the combustion of fuels [3–5].

As a result, the potential $CO_2$ emissions reductions through energy efficiency and renewable fuels are limited, while the cement industry faces an urgent challenge of reaching a $CO_2$ reduction target of 80 % by 2050 [6,7]. According to the European Cement Association (Cembureau), Carbon Capture, Utilization and Storage (CCUS) has the potential to reduce 42 % of the cement industry's $CO_2$ emissions in Europe by 2050 (Fig. 1) [8].

In this paper, a methodology, discussed in Section 2, is applied, to identify the most promising technologies to decarbonise the cement manufacturing process, making use of the Portuguese case study.

Cement is an important industrial sector in the Portuguese economy, and the six cement manufacturing units of mainland Portugal, operated by two private companies (Secil and Cimpor), export approximately 50 % of its production [9,10].

*Abbreviations:* AHP, Analytic Hierarchy Process; ATIC, Portuguese cement industry representative body; Avg, Average; CaL, Calcium Looping; CAPEX, Capital Expenditures; CCUS, Carbon Capture, Utilization and Storage; CEPCI, Chemical Engineering Plant Cost Index; CR, Consistency Ratio; ECRA, European Cement Research Academy; ETS, Emissions Trading Systems; HECLOT, High Efficiency Calcium Looping Technology; IRR, Internal Rate of Return; KPIs, Key Performance Indicators; LCA, Life Cycle Assessment; MCDM, Multi-Criteria Decision Making; MEA, Monoethanolamine; NG, Natural Gas; NPV, Net Present Value; O&M, Operation and Maintenance; OPEX, Operational Expenditures; Ref, Reference Cement Plant; SPEC, Specific Primary Energy Consumption; SPECCA, Specific Primary Energy Consumption per $CO_2$ Avoided; TEA, Techno-Economic Assessment; TRL, Technology Readiness Level; WSM, Weighted Sum Model.

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https://doi.org/10.1016/j.jcou.2022.102375
Received 6 September 2022; Received in revised form 14 December 2022; Accepted 15 December 2022

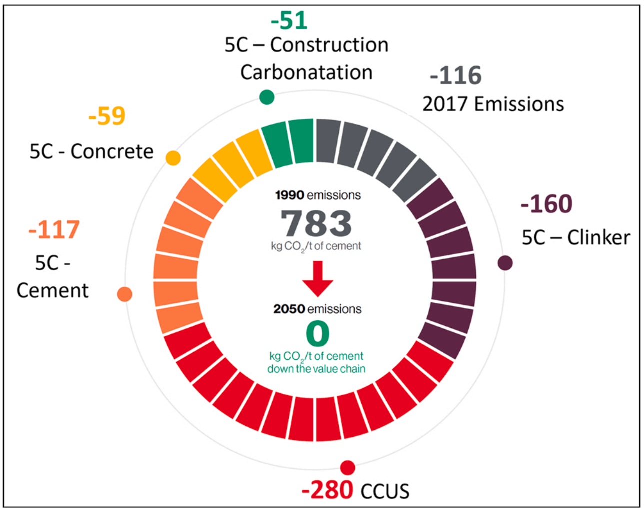


**Fig. 1.** $CO_2$ reduction goals by 2050 for the cement value chain [8].

This is a realistic case study, as the Portuguese National Low Carbon Roadmap 2050 considers the adoption of CCUS by the cement industry as a cost-effective option in Portugal. It suggests that carbon neutrality is to be achieved through CCUS if cement production levels increase, and that by 2050, 68 % of Portuguese clinker is predicted to be produced with CCUS [11].

The relevance of CCUS was later confirmed by the national Carbon Capture and Storage roadmap for Portugal and emphasized by the ongoing Strategy CCUS European Project, which highlighted that the cement industry should be the primary target for CCUS in the Lusitanian basin [9,12]. Subsequently, the Portuguese Carbon Neutrality Roadmap 2050 for the cement industry, launched in March 2021, pointed for the adoption of CCUS to be the only option available to reduce the remaining 35 % of the total $CO_2$ emissions by 2050, after the complementary measures implementation [4]. However, the potentially adverse physical and economic consequences of altering the cement chemical nature have been an obstacle in the incorporation of breakthrough technologies that might affect clinker composition [13].

The trade-offs between environmental and economic benefits are particularly relevant as no $CO_2$ capture technology has yet reached commercial scale demonstration in the cement industry. Still, there are some large scale projects at different development stages, including the Longship Project, which is implementing an amine-based technology to capture 0.4 Mt $CO_2$/year by 2023, and a pilot-scale calcium looping (CaL) plant using High Efficiency Calcium Looping Technology (HECLOT) to capture 0.1 Mt $CO_2$/year by 2024. Oxyfuel combustion has not been demonstrated at such large scale, however, the ongoing phase IV of the European Cement Research Academy (ECRA) project might include the demonstration of this technology at industrial scale [14].

Currently, the focus of the literature has been on post-combustion through chemical absorption with amine solutions. Aqueous solutions of alkanolamines, such as monoethanolamine (MEA), are widely used in the chemical and gas industries, although on a much smaller scale than would be required in the cement industry. The development of second generation solvents has led to substantial energy savings in the power sector; however, its application in the cement sector is still being investigated [14–19]. Fewer studies have been conducted on CaL post-combustion [20–23], and oxyfuel $CO_2$ capture technologies [17,19,24].

Comprehensive work has been performed in each of the technologies, but there is no literature addressing the integrated Life Cycle Assessment (LCA) and Techno-Economic Assessment (TEA) adopted here for these 3 technologies in the cement industry. In fact, a consistent evaluation of more than two types of $CO_2$ capture technologies for the cement industry is rarely available, with the only exceptions found in [19,25,26].

This paper therefore provides a new analysis making use of a multi-criteria decision making (MCDM) based on a LCA and TEA integrated with the Analytic Hierarchy Process (AHP) and Weighted Sum Model (WSM). It provides a systematic analysis of the MEA and CaL post-combustion capture and oxyfuel technologies implementation, demonstrating their use for the case study of the Portuguese cement industry. Consistent assumptions and specific techno-economic and environmental key performance indicators (KPIs) are used for direct comparison considering alternative scenarios (worst, intermediate and best-case).

## 2. Methodological framework

The methodological framework developed builds on the integrated TEA and LCA standardized methodological frameworks for $CO_2$ utilization [27,28]. The first step consists of defining the goal and scope of the analysis. This is followed by establishing an inventory phase where techno-economic and environmental data are collected. Mass and energy balances are conducted considering the cement plant with and without $CO_2$ capture technologies. This data is used as input for economic and environmental evaluations of the technologies. The total costs (operational expenditures (OPEX), $CO_2$ and capital expenditures (CAPEX)) and the net $CO_2$ avoided costs are calculated for a cement plant with and without $CO_2$ capture, and three different scenarios are assessed. Based on these costs and on the mass and energy balances, relevant KPIs are calculated.

The interpretation of the technical, economic, and environmental goals is addressed for each scenario through the MCDM method based on the integrated WSM approach using the AHP method to evaluate the three criteria (technical, economic, and energy / environmental) and KPIs weights. Finally, the ranking of the $CO_2$ capture options, including the reference cement plant, is reported for each scenario.

The goal is to rank three distinct $CO_2$ capture technologies, based on their techno-economic feasibility and environmental impacts, and compare them with an option without $CO_2$ capture, using a Portuguese cement industry case study.

In the formulas used, the variable $t$ is the year (between 2028 and 2055), the variable $x$ represents the scenario (worst, intermediate, or best-case) and the variable $y$ the $CO_2$ capture option.

The $CO_2$ capture technology options applied to a reference cement plant, schematically represented in Fig. 2, are:

- No $CO_2$ capture: “Ref”.
- MEA post-combustion $CO_2$ capture: “MEA”.
- Oxyfuel combustion $CO_2$ capture: “Oxyfuel”.
- CaL post-combustion $CO_2$ capture: “CaL”.

A “cradle-to-gate” boundary was adopted as each of the options produces the same product (clinker) and the subsequent transport and use or storage of $CO_2$ does not depend on the $CO_2$ capture technology used. The methodology implemented is to be used for designing policy instruments and to guide cement companies in the definition of their investment priorities. The functional unit used was “1 t of clinker”.

Three different scenarios based on 4 key parameters that reflect the context in which the industry may operate, from the point of view of the feasibility of the $CO_2$ capture plant (worst, intermediate, and best-case) were characterised, as indicated in Table 1. Note that the exact parameters that characterise each scenario are detailed throughout the paper.

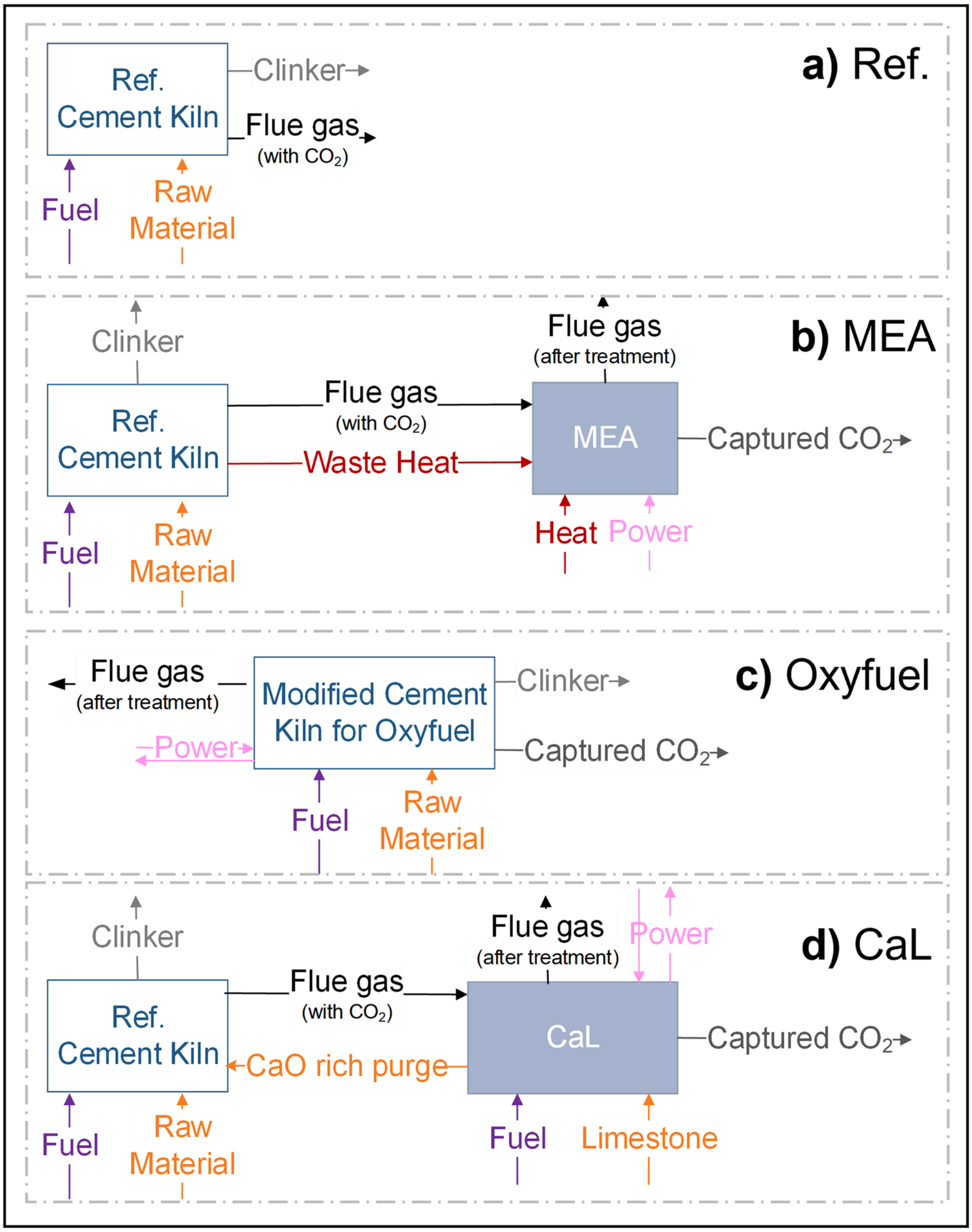


**Fig. 2.** Schematic overview of investigated technologies. Based on [29].

**Table 1**
Parameters considered for each scenario.

| Parameter/ Scenario | Worst | Intermediate | Best | Exact values |
|---|---|---|---|---|
| $CO_2$ Price | Low | Medium | High | Fig. 6 |
| Cement Price | Low | Medium | High | Table 3 |
| CAPEX | High | Medium | Low | Fig. 8 |
| OPEX | High | Medium | Low | Supplementary Information |

The objective is to make use of this methodology to respond to the following questions:

1. Which option is most economically viable to implement?
2. Which option is more environmentally friendly to implement?
3. What is the easiest technology to retrofit to an existent cement plant?
4. Overall, which technology is recommended for retrofitting an existent cement plant in Portugal considering questions 1–3?

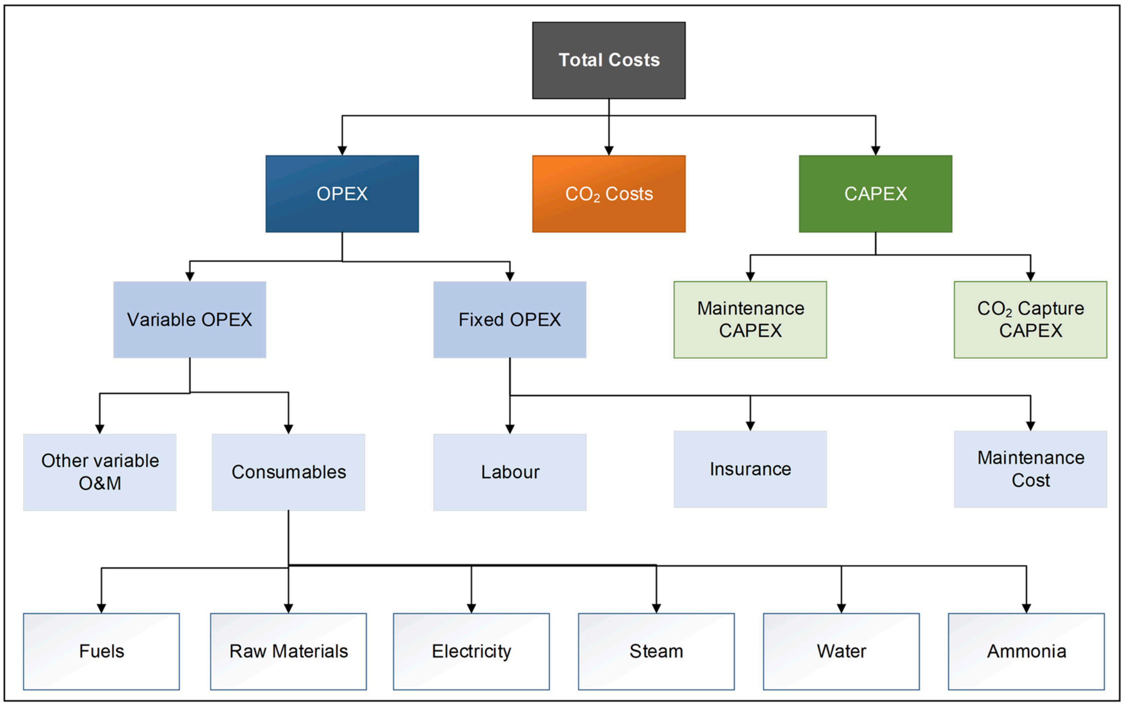


**Fig. 3.** Total cost breakdown.

**Table 2**
Data quality assessment (P = primary; S=secondary; B=both).

| Data | OPEX | | | | | | | | $CO_2$ Costs | CAPEX | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fuel | Raw Material | Electricity | Steam | Water | Ammonia | Other | Fixed | | Maintenance | $CO_2$ Capture |
| Balances | B | B | P | S | S | P | S | S | S | P | S |
| Prices | B | S | S | S | S | S | S | S | | | |

## 2.1. Data quality

One of the most important steps in this methodological framework is to specify the data to be collected and the main assumptions to be considered. Data quality varies depending on the source, which can be divided into primary, when the data is collected locally, and secondary, if the data is obtained from published sources and databases. The cost assessment methodology is mainly based on estimations of the OPEX, $CO_2$ costs, and the CAPEX, as described in Fig. 3. Note that $CO_2$ storage and transportation costs are not included.

The variable OPEX includes utilities consumption, such as raw materials, fuels, electricity, and water. Although the variable OPEX should also include the $CO_2$ costs, these are calculated separately to isolate the impact of $CO_2$ prices. Table 2 summarizes the data quality assessment.

Here, all economic data is reported on a 2020 basis. In cases where costs are not directly available in 2020 prices, they are adjusted through the Chemical Engineering Plant Cost Index (CEPCI) as indicated in Eq. 1 [30].

$$C = C_0 \times \left(\frac{CEPCI}{CEPCI_0}\right) \quad (1)$$

Where:

- C= Cost in 2020 [€].
- $C_0$= Base cost [€].
- CEPCI=CEPCI in 2020 (596.2) [31].
- $CEPCI_0$=Base CEPCI.

A discounted cash flow approach is considered to perform the project

**Table 3**
Fixed assumptions (secondary data).

| Scenario/ Technology | Parameters | Unit | Value | Reference |
|---|---|---|---|---|
| All types | Operational Lifetime | Years | 25 (2031–2055) | [9,19] |
| | Construction Time | Years | 3 (2028–2030) | [19] |
| | Tax Rate | % | 22.5 | Sum between the nominal rate of 21 % and the municipal surcharge of 1.5 % reported by Secil [32,33]. |
| | Discount Rate | % | 8.0 % | Rate calculated in [19]. This value is lower than Secil's reported weighted average (Avg) cost of capital [33]. |
| Worst | Cement Price | €/$t_{cement}$ | 93 | [34] |
| Intermediate | | | 102 | |
| Best | | | 116 | |
| Ref | $CO_2$ Capture Rate | | 0 | [19] |
| MEA | | | 0.90 | |
| Oxyfuel | | | 0.90 | |
| CaL | | | 0.94 | |

**Table 4**
Annual allocation of $CO_2$ capture CAPEX [35].

| Allocation of $CO_2$ capture unit costs [%] | Time | Year |
|---|---|---|
| 40 | -2 | 2028 |
| 30 | -1 | 2029 |
| 30 | 0 | 2030 |

valuation with a discount rate of 8 %, as calculated by [25]. It is assumed that all clinker is consumed to produce cement. The fixed assumptions adopted for the different scenarios and technologies are summarized in Table 3 and Table 4. The assumed annual CAPEX allocation is indicated in Table 4 [35].

The clinker to cement ratio and the $CO_2$ production per unit of cement are expected to decrease throughout the years. The Portuguese data was based on the Portuguese cement industry representative body (ATIC) carbon neutrality roadmap targets for the clinker phase for 2020, 2030 and 2050 [4]. The values were interpolated between these years and extrapolated for the remaining years, as depicted in Fig. 4. It should be noted that although the target is to reach 0 emissions by 2050, that includes the overall cement value chain represented in Fig. 1 [8].

### 2.2. Mass and energy balance

Cement manufacturing is a resource-intensive process that consumes high volumes of raw materials. According to ATIC, 1.425 tonnes of raw materials are consumed per tonne of clinker (primary data). An overview of the main formulas, a detailed description and quantification of each raw material type, and overall costs can be found in the Supplementary information. Raw materials consumption is the same for all $CO_2$ capture technologies, apart from CaL, as in this technology, the solids removed from the calciner, mainly composed of CaO, are incorporated into the cement preheater, partially substituting the raw meal needed for clinker production [25]. A reduction in raw materials consumption of 2.46 % was assumed based on [19], which corresponds to a total consumption of 1.39 $t/t_{clinker}$.

Various fuels can be used to provide the thermal energy demand needed for the clinker burning process [5]. The energy consumption for each fuel was calculated according to Eq 2.

$$\text{Energy\_Consumption}\left[\frac{GJ}{t_{clinker}}\right] = \text{Fuel\_Consumption}\left[\frac{t}{t_{clinker}}\right] \times \text{Heat\_of\_Combustion}\left[\frac{GJ}{t}\right] \quad (2)$$

Table 5 specifies the average energy consumption of each fuel in the Portuguese cement industry based on the weighted average fuel consumption of the Portuguese cement plants, provided by ATIC (primary data), and on the heat of combustion values from Ecoinvent v3.5 (secondary data) [38], resulting in a total of 3.74 $GJ/t_{clinker}$.

**Table 5**
Specific fuel and energy consumption for the Ref.

| Type | Fuel | Heat of Combustion [GJ/t] | Fuel consumption [$t/t_{clinker}$] | Energy consumption [$GJ/t_{clinker}$] |
|---|---|---|---|---|
| Fossil Fuels | Petcoke | 28.6 | 0.0777 | 2.223 |
| | Fuel oil | 43.7 | 0.0003 | 0.015 |
| Alternative | Rubber and tires | 27.2 | 0.0048 | 0.132 |
| | Refuse-derived fuel | 23.0 | 0.0184 | 0.424 |
| | Regular Industrial Waste | 23.0 | 0.0328 | 0.755 |
| | Hazardous Industrial Waste | 23.0 | 0.0011 | 0.026 |
| | External Hazardous Industrial Waste | 40.1 | 0.0006 | 0.024 |
| Biomass | Vegetable Biomass | 19.4 | 0.0054 | 0.105 |
| | Animal Biomass | 15.0 | 0.0017 | 0.026 |
| | Charcoal | 29.3 | 0.0001 | 0.002 |
| | Wood | 19.4 | 0.0002 | 0.004 |
| Reference | ATIC | [38] | ATIC | Eq 2 |

The indicated thermal energy consumption applies to all $CO_2$ capture technologies. However, MEA needs a considerable amount of heat for solvent regeneration. Moreover, CaL requires increased fuel consumption, assumed to be supplied by natural gas (NG) instead of coal, as usually reported in the literature [25,39].

The data for the total average electricity used in the Portuguese cement industry was quantified as 0.467 $MWh/t_{cement}$ by ATIC. For the "Ref inventory", it was assumed that 46.7 % of the total electricity was consumed in the clinker phase (0.0689 $MWh/t_{clinker}$) based on [40]. This value is higher for the MEA technology, which requires fans and pumps in the core process as well as for compression and dehydration of the captured $CO_2$ [25,29]. For both CaL and oxyfuel, there is additional electricity consumption, due to air separation and $CO_2$ purification units, which can be partially recovered as waste heat. In fact, for CaL, the electricity generated by a steam cycle using waste heat in the process is

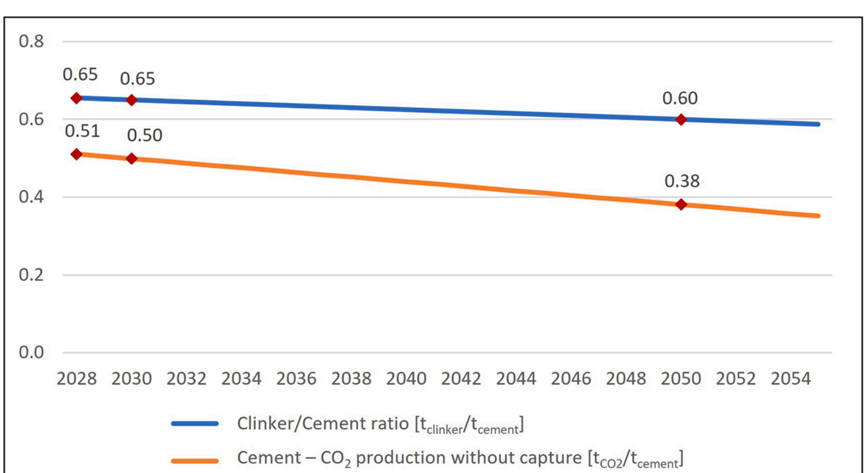


**Fig. 4.** Clinker/cement and reference $CO_2$ production assumed ratios per year. Based on [4,36,37].

**Table 6**
Added $CO_2$ data.

| Consumable | Added Energy Consumption [$GJ/t_{clinker}$] | | | Reference | Emission Factor [$t_{CO2}/GJ$] | Reference |
|---|---|---|---|---|---|---|
| | MEA | Oxyfuel | CaL | | | |
| NG | 0 | 0 | 3.86 | [19,25] | 0.056 | [41] |
| Steam from NG | 3.07 | 0 | 0.00 | | 0.056 | [41] |
| Net electricity | 0.89 | 1.17 | -0.58 | | 0.064 | [42] |

**Table 7**
Category and questions associated with each KPI.

| Question | KPI Category | KPI | Units | Scenario dependent? |
|---|---|---|---|---|
| 1 + 4 | Economic | Total costs | €/ $t_{clinker}$ | Yes |
| | | Net Present Value (NPV) | €/ $t_{clinker}$ | |
| | | Internal Rate of Return (IRR) | % | |
| | | Payback Period | years | |
| 2 + 4 | Energy/ Environmental | Net $CO_2$ Emissions | $t_{CO2}/t_{clinker}$ | No |
| | | Net $CO_2$ Avoided | NA | No |
| | | Net $CO_2$ Avoided Costs[1] | €/$t_{CO2}$ | Yes |
| | | Specific Primary Energy Consumption (SPEC) | GJ/ $t_{clinker}$ | No |
| | | SPEC to Avoid $CO_2$ Emissions (SPECCA)[2] | GJ/ $t_{CO2}$ | |
| 3 + 4 | Technical | Plant Operability and Clinker Quality Risk | NA | No |
| | | Space Constrains | NA | |
| | | Safety | NA | |
| | | Technology Readiness Level (TRL) | NA | |

[1]The average $CO_2$ price was assumed for the Reference as the value would be 0/0, which is an indeterminate form.
[2]The SPECCA value can be used to compare the technologies but only the SPEC value can be used to compare all the options, as the Reference value would be 0/0.

higher, resulting in a negative net electricity consumption [19,25].

The added $CO_2$ emissions associated with each technology when compared to the Reference, were calculated, as indicated in Eq 3, through the product between the emission factor and the added energy consumption/production (values presented in Table 6), which is positive if there is energy consumption and negative when there is energy production (from the point of view of the cement plant).

$$(\text{Added\_CO}_2)_y\left[\frac{t_{CO2}}{t_{clinker}}\right] = (\text{Added\_Energy})_y\left[\frac{GJ}{t_{clinker}}\right] \times \text{Emission\_Factor}\left[\frac{t_{CO2}}{GJ}\right] \quad (3)$$

In terms of results assessment, 12 KPIs were defined and grouped into 3 categories - economic, energy/environment and technical - to assess the four $CO_2$ capture options according to the four questions defined, as summarized in Table 7. Note that some of the KPIs depend on the scenario.

Petcoke's and alternative fuel prices were provided directly by the national stakeholders of the Portuguese cement industry (primary data). The remaining fuel prices were calculated using Eq 4. The average fuel price in Portugal in 2019 and the typical heat of combustion were obtained from the literature (secondary data) [38,43].

$$\text{Fuel\_Price}\left[\frac{€}{GJ}\right] = \frac{\text{Average\_Fuel\_Price\_in\_Portugal\_}in\text{\_2019}\left[\frac{€}{t}\right]}{\text{Typical\_Heat\_of\_Combustion}\left[\frac{GJ}{t}\right]} \times \left(\frac{CEPCI_{2020}}{CEPCI_{2019}}\right) \quad (4)$$

The fixed OPEX, indicated in Fig. 5, includes labour costs (operating, administrative and support), the total annual insurance cost and maintenance costs (preventive maintenance, periodic replacement of materials and corrective maintenance such as repair and replacement of failed components) [19].

The European Union (EU) Emissions Trading System (ETS) carbon prices are expected to increase over the years. The values assumed were based on the minimum, average and maximum prices projected by the High-Level Commission on Carbon Prices for 2020, 2030 and 2050 [44].

A linear interpolation method was used to predict the values between 2028 and 2050 and extrapolated in the other years.

The $CO_2$ price, paid in full by the companies, was assumed to be 60 % of the EU ETS considering the greenhouse gas permits by 2026, which increases linearly to 100 % of the EU ETS by 2030 onwards (medium and high scenarios) or by 2035 (low scenario). This assumption is the main source of uncertainty, despite being based on the Portuguese legislation and environmental regulator [45,46]. The assumed values of EU ETS and $CO_2$ prices for the different scenarios are specified in Fig. 6.

CAPEX was calculated considering the investment needed to implement each $CO_2$ capture technology and the maintenance CAPEX, which is the minimum amount of capital expenditure required to be replaced to maintain current operations [47]. Maintenance CAPEX was based on Secil data, after its normalization using the annual production of national clinker, as shown in Fig. 7. Note that in 2016, the maintenance CAPEX was higher due to the purchase of production assets in an international tender.

The maintenance CAPEX considered in the calculations was

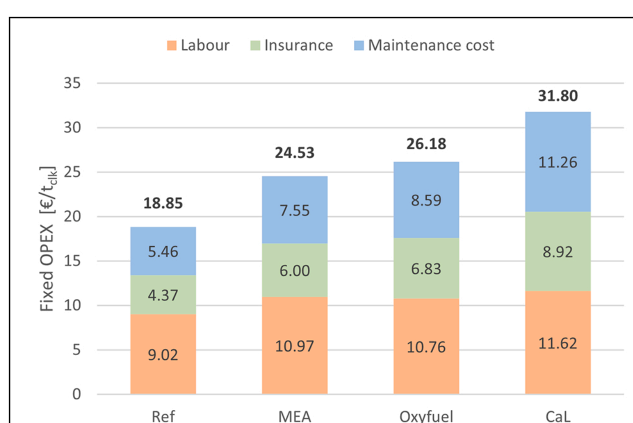


**Fig. 5.** Fixed OPEX for technology. Based on [19].

$6.66 \pm 2.00$ €$/t_{clinker}$, which corresponds to the average value and the standard error. $CO_2$ capture CAPEX for the intermediate scenario was based on [19] and converted into 2020 prices with a margin of +35/−15 % (worst and best-case scenarios, respectively).

The assumed CAPEX per scenario and technology is indicated in Fig. 8.

NPV is the sum of CAPEX, OPEX, $CO_2$ costs and Revenue during the construction period and operational lifetime of the project as shown in Eq 5 [52,53]. Related to the NPV calculation is the IRR, which is the interest rate that equates the NPV to zero. To accept an investment project, it is considered that the IRR must be greater than the discount rate [54,55].

$$NPV = \sum_{t=i}^{n+N} \frac{Revenue_t}{(1+r)^t} + \sum_{t=i}^{n+N} \frac{OPEX_t}{(1+r)^t} + \sum_{t=i}^{n+N} \frac{CO_2Costs_t}{(1+r)^t} + \sum_{t=i}^{n} \frac{CAPEX_t}{(1+r)^t} \quad (5)$$

Where:

- $i$=Starting year (2028).
- $r$=Discount rate (8 %).
- $n$= Construction years, from 2028 to 2030.
- $N$= Operational years, from 2031 to 2055.
- OPEX, CAPEX and $CO_2$ costs are negative.

The payback period is one of the most common decision tools available and can be defined as the period, in years, which it takes for the project's net cash inflows to recoup the original investment. When the options are mutually exclusive, from an economic point of view, the project with the shorter payback period should be selected. However, payback period does not measure overall project worth because it does not consider cash flows after the payback period [56].

The Average Net $CO_2$ Emissions, in $t_{CO2}/t_{clinker}$, is defined as the average annual difference between the net $CO_2$ emissions of the clinker production without $CO_2$ capture (Ref) and with $CO_2$ capture, as indicated in Eq 6.

$$(Avg\_Net\_CO_2Emissions)_y = \frac{\sum_{t_0}^{t_f}\left((Ref\_CO_2Emissions)_t + (Total\_Added\_CO_2)_{t,y} - (Total\_CO_2Captured)_{t,y}\right)}{t_f - t_0} \quad (6)$$

Where:

- $t_0$= initial year of the project (2031).
- $t_f$= final year of the project (2055).

The Net $CO_2$ Avoided index, defined in Eq 7, in %, measures the total net $CO_2$ emissions avoided in the cement plant due to the integration of technology $y$ compared to Reference through the ratio of the total net $CO_2$ avoided, in $t_{CO2}/t_{clinker}$, and the average $CO_2$ emissions without $CO_2$ capture, in $t_{CO2}/t_{clinker}$.

$$(Net\_CO_2Avoided)_y = \frac{Avg\_Reference\_CO_2Emissions - (Avg\_Net\_CO_2Emissions)_y}{Avg\_Reference\_CO_2Emissions} \quad (7)$$

The Net $CO_2$ Avoided Cost, indicated in Eq 8, in €$/t_{CO2\ avoided}$, is defined as the quotient between the total added costs, in €$/t_{clinker}$, and the total net $CO_2$ avoided, in $t_{CO2}/t_{clinker}$.

$$[Net\_CO_2Avoided\_Cost]_{x,y} = \frac{\left[\sum_{t_0}^{t_f} Total\_Costs\_with\_Capture\right]_{x,y} - \left[\sum_{t_0}^{t_f} Total\_Costs\_without\_Capture\right]_x}{(Total\_Net\_CO_2Avoided)_y} \quad (8)$$

The SPECCA index, in $GJ/t_{CO2}$, is defined by the ratio between the difference in the SPEC of fuels and electricity at the cement plant with and without $CO_2$ capture, in $GJ/t_{clinker}$, and the net $CO_2$ avoided emissions, in $t_{CO2}/t_{clinker}$, as indicated in Eq 9.

$$(SPECCA)_y = \frac{[Total\_Primary\_Energy\_used\_with\_Capture]_y - Total\_Primary\_Energy\_used\_without\_Capture}{(Total\_Net\_CO_2Avoided)_y} \quad (9)$$

Several aspects are important for the evaluation and practical implementation of retrofitting technologies to capture $CO_2$ in a cement plant [57]. The majority of the technical indicators to assess the retrofitability of the $CO_2$ capture technology to an existing cement plant are based on a semi-qualitative assessment, using a scale from 1 to 5, where the retrofit:

1. Is not required (Reference cement plant).
2. Is straightforward.

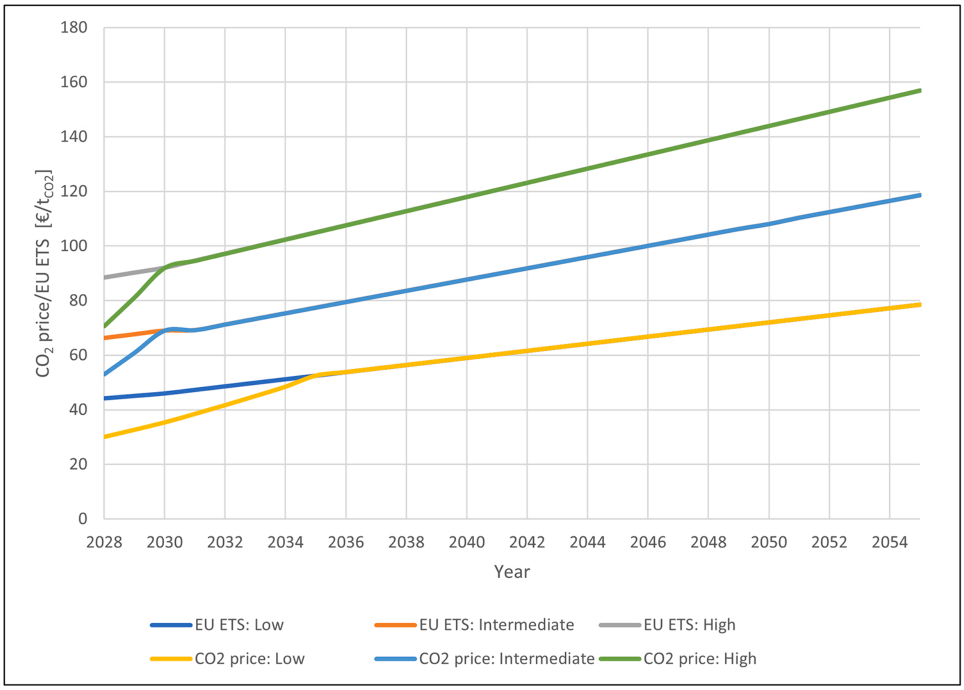


**Fig. 6.** EU ETS and $CO_2$ price assumed values (secondary data). Based on [44–46].

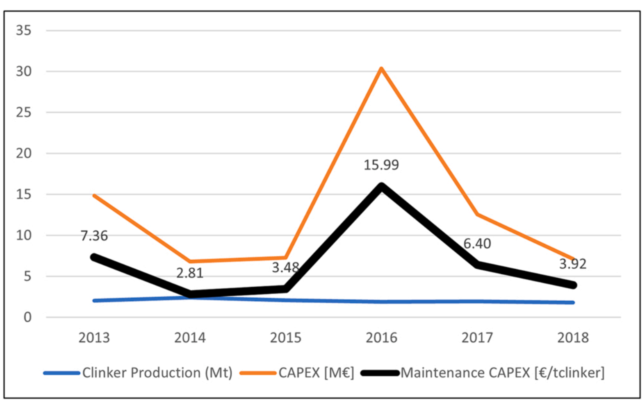


**Fig. 7.** Secil's normalized annual CAPEX (primary data). Based on [33,48–51].

3. Is mostly straightforward, but some attention is needed.
4. Requires more attention, or important aspects are unknown, so further research is needed.
5. Is unable to be implemented.

The technical KPIs to be assessed are summarized in Table 8.

## 3. Results and discussion

The results obtained are divided into four sections, according to the defined questions.

### 3.1. Economic KPIs

The total costs calculated for each scenario and technology is represented in Fig. 9.

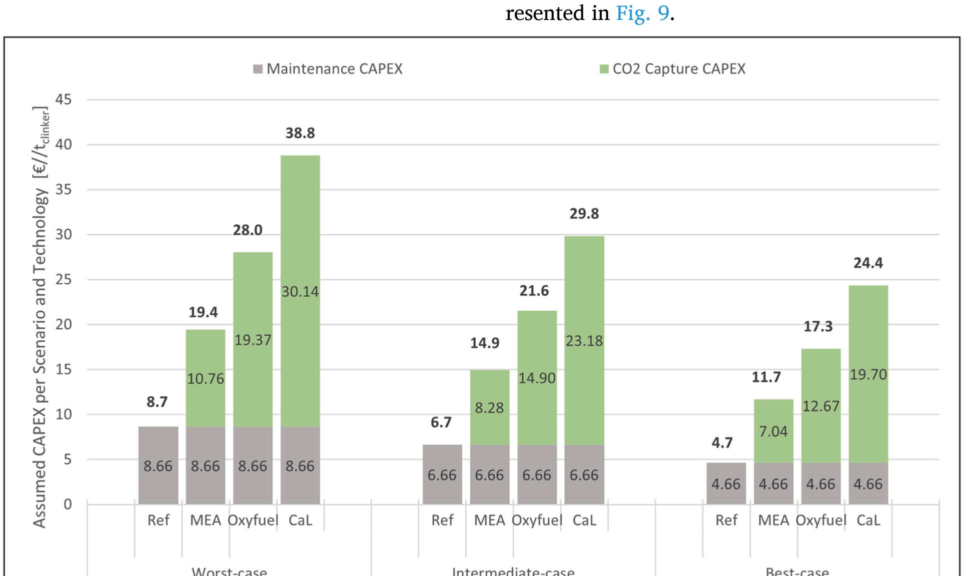


**Fig. 8.** Assumed CAPEX per scenario and technology. Based on [19,33,48–51].

**Table 8**
Technical KPIs explanation.

| KPI | Explanation | Scale |
|---|---|---|
| Plant Operability and Clinker Quality Risk | Analysis the influence of the installation of a $CO_2$ capture system in the operability of the plant and the quality of the product. Some technologies imply modifications of the kiln system itself, increasing the risk for effects on plant operability or product quality. | 1–5 |
| Space Constraints | Analysis the space and location required for the application of $CO_2$ capture technologies in cement plants. | |
| Safety | Evaluates the introduction of new chemicals or subsystems at the plant as they may lead to new procedures to ensure safe operation or the need to require additional permits. Constraints related to the handling of $CO_2$ at the plant are the same for all technologies, apart from the Reference. | |
| TRL | The TRL scale measures the maturity of a technology[58]. | 1–9 |

The weight of the consumables and other operation and maintenance (O&M) costs in the variable OPEX for each scenario and technology, is represented in Fig. 10.

Fig. 9 shows that the Reference cement plant presents a total cost of 105 €/$t_{clinker}$,115 €/$t_{clinker}$ and 124 €/$t_{clinker}$ for the worst, intermediate and best-case scenario, respectively. This difference is mainly explained by $CO_2$ costs, which more than doubled from the worst (41 €/$t_{clinker}$) to the best scenario (84 €/$t_{clinker}$). The CAPEX and variable OPEX decrease from the worst to the best-case scenario, the latter mainly due to the reduction in fuels and electricity costs as revealed in Fig. 10. However, this decrease is not sufficient to offset the increase in $CO_2$ costs, leading to an increase in the total costs from the worst to the best-case scenario.

Moreover, MEA's total costs are always higher than the alternatives, regardless of the scenario. On the other hand, the relative difference in

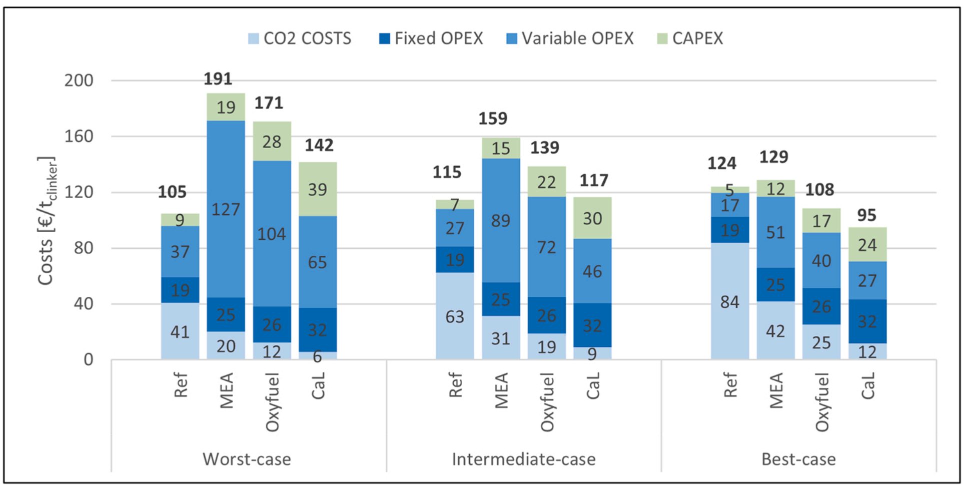


**Fig. 9.** Total costs [€/$t_{clinker}$].

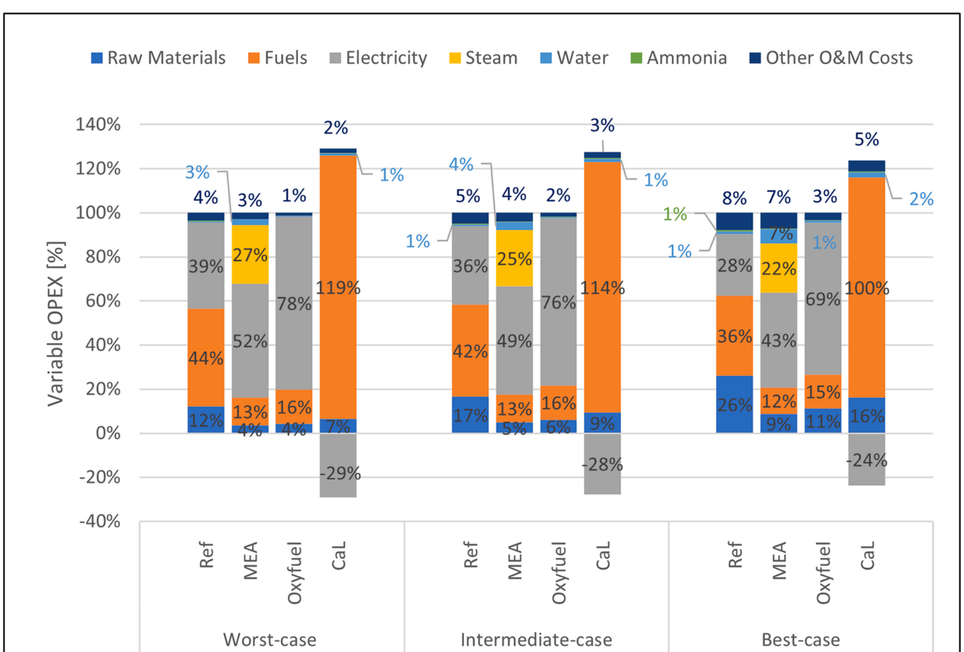


**Fig. 10.** Average OPEX [%]. The values below 1 % are not shown.

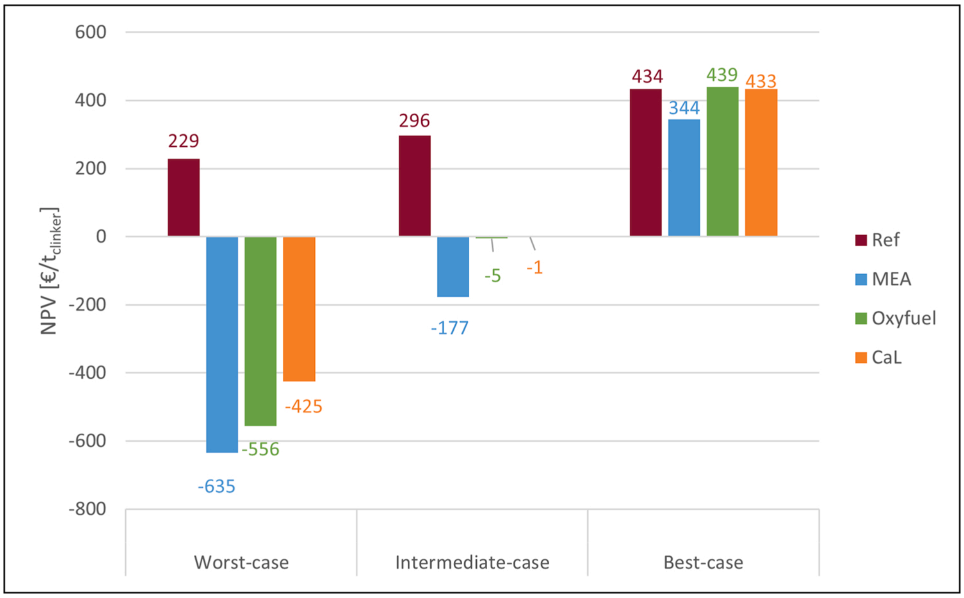


**Fig. 11.** NPV [€/$t_{clinker}$].

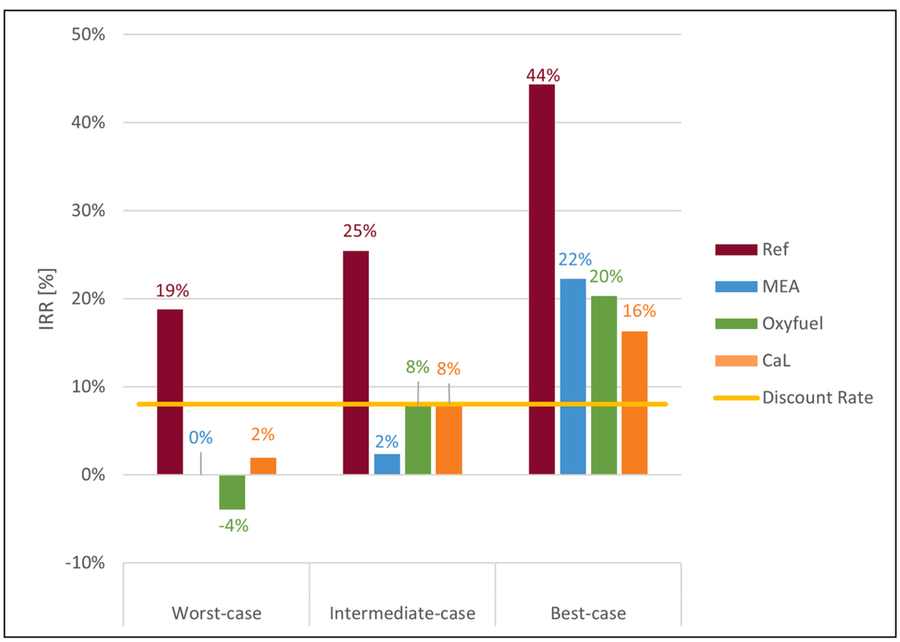


**Fig. 12.** IRR [%].

the total costs between the Reference and both the CaL and oxyfuel $CO_2$ capture depends on the scenario. The costs are higher than the Reference in the worst (by 35 % for CaL and 63 % for oxyfuel) and intermediate scenarios (by 2 % for CaL and 21 % for oxyfuel) but lower in the best-case scenario (by 31 % for CaL and 15 % for oxyfuel). CaL has a higher fixed OPEX and CAPEX compared to the oxyfuel, however, the total costs are inferior as the variable OPEX is significantly lower due to the electricity production which covers the $CO_2$ capture process demand and part of the cement kiln demand, leading to the negative cost of electricity indicated in Fig. 10.

$CO_2$ costs are highest for Reference (as expected), followed by MEA, oxyfuel and CaL due to the difference in the total net $CO_2$ avoided. Overall, these results indicate that the cost-benefit of the $CO_2$ capture retrofit of an existing Portuguese cement plant is significantly dependent on the $CO_2$, electricity, and fuel costs.

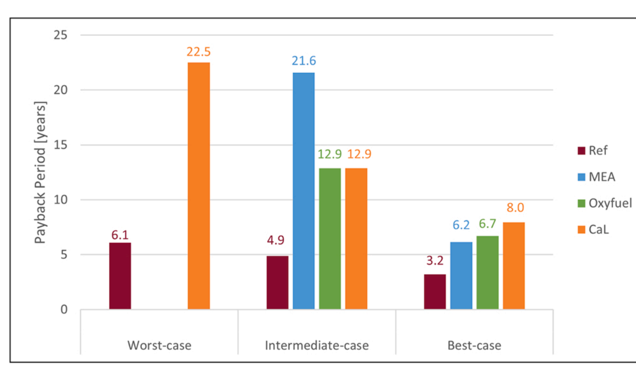


**Fig. 13.** Payback period [years].

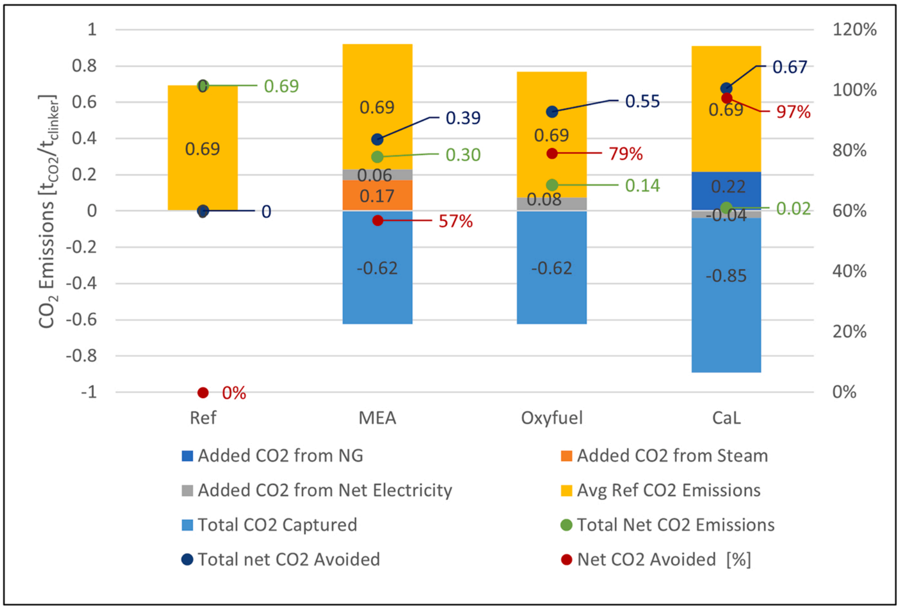


**Fig. 14.** $CO_2$ emissions, in $t_{CO2}/t_{clinker}$ and %.

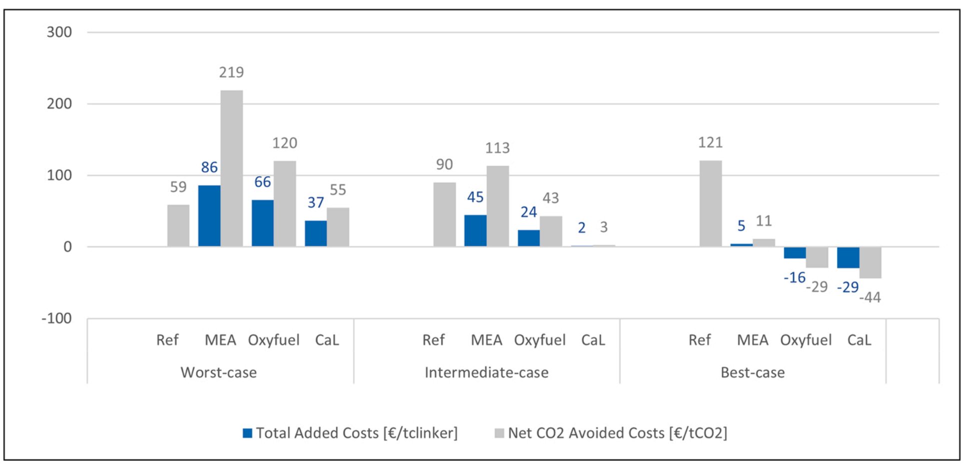


**Fig. 15.** Total added and net $CO_2$ avoided costs.

The NPV, in €/$t_{clinker}$, obtained for the studied scenarios and technologies is indicated in Fig. 11.

Fig. 11 indicates that, regardless of the scenario, the NPV of Reference is positive, which is a clear sign of economic viability as it determines that on top of recovering the investment (maintenance CAPEX)

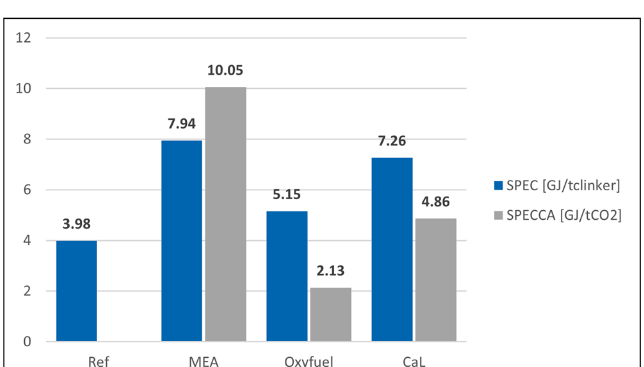


**Fig. 16.** SPEC and SPECCA.

and fulfilling the minimum income required by investors, a financial surplus is generated. On the other hand, the results show that the NPV of the $CO_2$ capture technologies is highly sensitive to the scenario. In the worst and intermediate-case scenarios, none of the options for $CO_2$ capture technologies is viable as they present a negative NPV value, which is lower in MEA, followed by oxyfuel and CaL. Contrastingly, in the best-case scenario, all $CO_2$ capture technologies investigated show a positive NPV, with oxyfuel's showing a highest value (439 €/$t_{clinker}$), slightly higher than both Reference (434 €/$t_{clinker}$) and CaL (433 €/$t_{clinker}$), which is followed by MEA (344 €/$t_{clinker}$). Consequently, the results show that, even with the increasing $CO_2$ costs in the intermediate scenario, the Reference plant is still the most viable option. The oxyfuel and CaL technologies only exhibit economic competitiveness in the best-case scenario. Still, current economic analysis does not consider the extra costs associated with the potential storage and transport of $CO_2$, nor the potential economic benefit of the $CO_2$ use. The IRR calculated for each scenario and technology is indicated in Fig. 12.

Fig. 12 shows that the IRR results are generally in line with the NPV results, as when the IRR is below the discount rate, the NPV is negative, and when the IRR is above this threshold, the NPV is positive. However, for the best-case scenario the highest IRR is obtained for Reference, followed by the MEA, oxyfuel and CaL while the NPV is highest for oxyfuel, followed by Ref, CaL and MEA. In this condition, the project with the higher NPV may be preferred as the IRR inherently assumes that any cashflow can be reinvested at the discount rate [59]. In this case, MEA should be considered the least viable option.

The payback period calculated for each scenario is indicated in Fig. 13. Note that in the worst-case scenario, the payback period of the MEA and oxyfuel $CO_2$ capture options is higher than the project's total lifetime and, for that reason, they are not represented in the graphic.

The results of the payback period are mostly aligned with the IRR obtained values. As such, an option with a higher IRR presents a lower payback period and vice versa. In the worst-case scenario, the payback period of the $CO_2$ capture technologies analysed, apart from CaL, is higher than the project's total lifetime, meaning that the costs would not be recovered during that period. The CaL has a payback period of 22.5 years, which is significantly higher than the Reference (6.1 years). In both the intermediate and best-case scenarios, the Reference presents a significantly lower payback period due to its lower CAPEX. MEA presents a payback period of 21.6 years in the intermediate-case scenario, which is considerably higher than the other technologies (12.9 years). In the best-case scenario, CaL presents the highest payback period (8.0 years), followed by oxyfuel (6.7 years), MEA (6.2 years) and finally Reference (3.2 years).

### 3.2. Energy and environmental KPIs

The total net $CO_2$ Emissions and the Net $CO_2$ Avoided KPIs depend on the Avg Reference $CO_2$ emissions, the captured $CO_2$ and the extra $CO_2$ emissions due to the implementation of the $CO_2$ capture technology from the additional net electricity consumption (in all technologies), steam (for MEA), and NG (for CaL). Fig. 14 contains the detailed results obtained for each technology.

The total net $CO_2$ Emissions were lower for CaL (0.02 $t_{CO2}/t_{clinker}$), followed by oxyfuel (0.14 $t_{CO2}/t_{clinker}$) and finally MEA (0.30 $t_{CO2}/t_{clinker}$) which are still significantly lower than Reference (0.69 $t_{CO2}/t_{clinker}$). Accordingly, the Net $CO_2$ avoided obtained was higher for CaL, followed by oxyfuel and MEA with 0.67 $t_{CO2}/t_{clinker}$ (97 %), 0.55 $t_{CO2}/t_{clinker}$ (79 %) and 0.39 $t_{CO2}/t_{clinker}$ (57 %), respectively.

Fig. 15 compares both the added costs of the clinker production with $CO_2$ capture and the Net $CO_2$ avoided costs. Following the definition of the Net $CO_2$ avoided costs of Eq 8, this value would be a mathematical indeterminate form for the Reference (0/0). As such, the average $CO_2$ price was assumed for each scenario according to Fig. 6. Note that a negative value represents savings associated with the implementation of a $CO_2$ capture plant compared to the Reference.

Fig. 15 shows that, regardless of the scenario, both the total added costs and the $CO_2$ Avoided costs are lower for the CaL, followed by oxyfuel and MEA. In the worst-case scenario, the total added costs for MEA and oxyfuel are 2.3 times and 1.8 times the CaL costs, respectively. As the Net $CO_2$ avoided is higher for the CaL, the Net $CO_2$ avoided costs are even higher for MEA (4.0 times) and oxyfuel (2.2 times) compared to the CaL. In the intermediate scenario, this difference accentuates, and MEA shows a total added cost 24.5 times higher than CaL (the Net $CO_2$ avoided costs are 42 times higher) while oxyfuel presents a total added cost 13 times higher (the Net $CO_2$ avoided costs are 16.1 times higher). Finally, in the best-case scenario, both the CaL and oxyfuel have a profit instead of a loss associated to the implementation of the technology. However, this does not apply to MEA, which presents a loss in every scenario.

The SPEC and SPECCA results are presented in Fig. 16. To compare the technologies investigated with the Reference, only SPEC was used, as SPECCA would be the mathematical indeterminate form of 0/0. As expected, the lowest SPEC value was obtained for the Reference (3.98 GJ/$t_{clinker}$).

The most important contributions to SPECCA differ across technologies. The highest value was obtained for the MEA technology (10.05 GJ/$t_{CO2}$). followed by CaL (4.86 GJ/$t_{CO2}$) while oxyfuel presented the lowest value (2.13 GJ/$t_{CO2}$). This is explained by a significantly lower SPEC (5.15 GJ/$t_{clinker}$) than the other technologies and a medium value for Net $CO_2$ avoided of 79 %. For oxyfuel, the added SPEC and reduction in Net $CO_2$ avoided are almost entirely due to the increased electricity consumption.

CaL technology presents a SPECCA value 2.3 times higher than oxyfuel. For this technology, the NG and net electricity consumption define the final SPECCA value. The considerable electricity generation is especially important as it contributes to the reduction of added SPEC and Net $CO_2$ avoided. In fact, the electricity generated covers the demand of the $CO_2$ capture process and part of the cement plant's demand.

MEA technology has the highest SPECCA value (10.05 GJ/$t_{CO2}$), which is 4.7 times the CaL's SPECCA. The SPEC related to the steam required in the process is responsible for most of the added net primary energy consumption and reduction of Net $CO_2$ avoided.

### 3.3. Technical KPIs

The technical evaluation is mainly based on the qualitative analysis of [57] and the current TRL of each $CO_2$ capture technology according to [14] (secondary data). A summary of the KPIs results, subjected to a scale of 1–5 as defined in Table 8, is given in Fig. 17.

#### 3.3.1. Plant operability and clinker quality risk

The application of MEA and CaL post-combustion technologies does not affect the clinker burning process nor the clinker quality, as they can

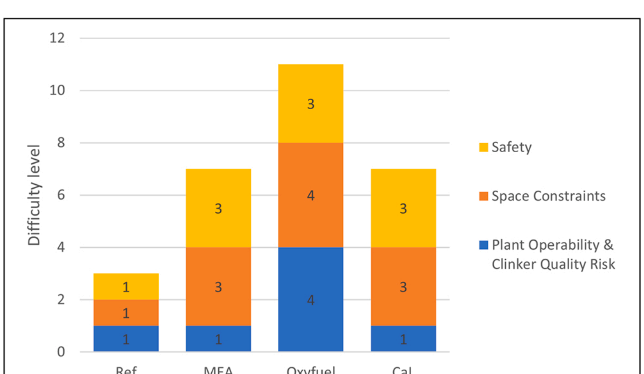


**Fig. 17.** Technical KPIs results.

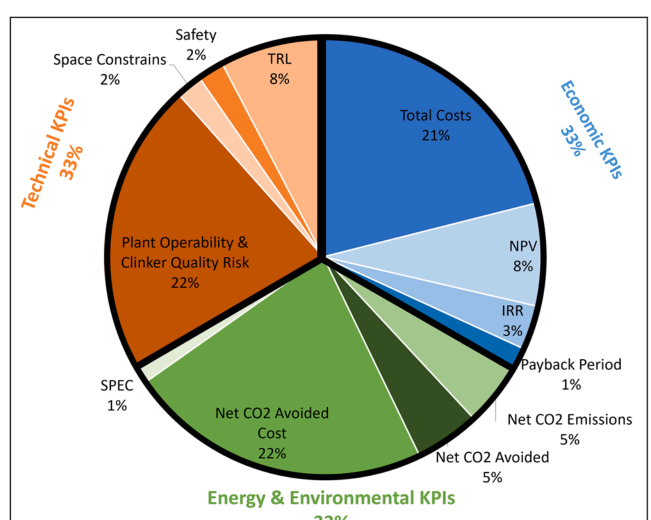


**Fig. 18.** Weight of each KPI obtained.

be installed as independent units. During the construction phase, only a short stop of the clinker production would be required to redirect the flue gas, which could be done during the annual maintenance period when the plant is shut down [57]. As such, the operability of the plant is not affected, and the technologies are given a score of 1, which is the same as Reference.

On the other hand, oxyfuel requires a significant modification of the cement production process, particularly in the clinker cooler, rotary kiln, calciner, and preheater. As a result, there is a risk of operational problems and clinker quality, which could result in additional post-treatment of the clinker and thus cost [60]. This technology therefore received a score of 4.

#### 3.3.2. Space constraints

There is a need for additional equipment and space to retrofit a cement plant with $CO_2$ capture, regardless of the process. The main difference between the technologies is the need for the equipment to be installed close to the kiln line [57].

For both MEA and CaL post-combustion technologies, the required equipment can be installed anywhere in the plant, and there is also some flexibility to split the systems and install different units at distinct locations in the plant, so these technologies are given a score of 3. The oxyfuel technology, however, is integrated with the kiln system itself, requiring space close to the kiln line, which justifies the given score of 4, contrasting with the score of 1 for Reference.

#### 3.3.3. Safety

The CaL and oxyfuel technologies require $O_2$, which could increase the risk of fires and explosions in the cement plant [57]. As such, its implementation may require a more complex permitting process and the establishment of new procedures and routines. Nevertheless, the use of oxygen is normal in many industries, so although attention is needed, it can still be handled, resulting in a score of 3.

The MEA process requires aqueous solutions of amines as a solvent. Amines and their degradation products are poisonous and dangerous for the environment. The use of these chemicals requires a permitting process and new procedures must be established to ensure safe operation in the plant [57]. As a result, a score of 3 is given for this technology, while Reference remains with the score of 1.

#### 3.3.4. TRL

The MEA process is the most mature capture technology, with a TRL of 8 in the cement industry, followed by CaL (TRL of 7) and finally oxyfuel (TRL of 6) [14]. The highest TRL (9) was assumed for the reference scenario.

### 3.4. Multi-criteria decision-making

Considering that $CO_2$ capture technologies are complex systems with numerous objectives and parameters, the most promising option is identified using MCDM methods. Based on a comparative analysis of MCDM methods [61], a WSM was chosen for this study. WSM is a transparent model in which the connections between inputs and outputs can be easily seen and interpreted, and the influence of decision-makers' preferences on the results is clear [62]. Simplicity and transparency are the key factors determining the choice of WSM as an evaluation method because the proposed model is designed for use and adjustment to local conditions by decision-makers who are not necessarily experts in MCDM. WSM is intuitive for decision-makers and does not require complicated calculation procedures.

Firstly, KPI values for each scenario were summarized for direct comparison between $CO_2$ capture options. Each indicator was weighted according to its importance using the AHP method, as shown in Fig. 18, with inputs from Portuguese cement companies' stakeholders considering a long-term vision. To weight the criteria, two workshops were held with the Portuguese cement companies' stakeholders to define the relation of criteria importance (i.e., weighed criteria) via comparisons in a pairwise manner. The consistency ratio (CR) obtained in the AHP was always below 0.1, which indicates that the AHP calculation can be considered consistent and acceptable [63,64].

Secondly, each KPI was normalized depending on the objective (maximize or minimize) as indicated in Eq 10 and Eq 11, respectively. The input data used to compute the performance matrix is presented in the Supplementary Information file.

$$\overline{r_{ij}} = \frac{r_{ij}}{\max r_{ij}} \tag{10}$$

$$\overline{r_{ij}} = \frac{\min r_{ij}}{r_{ij}} \tag{11}$$

Where:

- max $r_{ij}$ = maximum value of indicator j with respect to alternative i.
- min $r_{ij}$ = maximum value of indicator j with respect to alternative i.

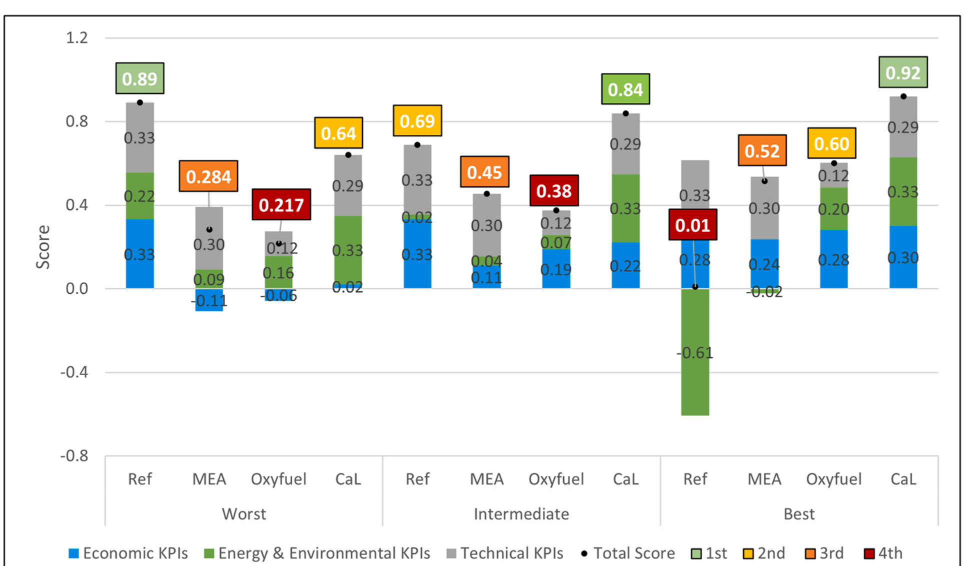


**Fig. 19.** Ranking of the $CO_2$ capture options (total and by category) for the studied scenarios.

The scores for each KPI were calculated by summing the weighted scores for each scenario, as indicated in the Supplementary Information file. Afterwards, the individual KPIs scores were divided into the 3 main categories and the final score ranked the options for each scenario from the highest (1$^{st}$ place) to the lowest (4$^{th}$ place), as indicated in Fig. 19.

In the economic dimension, the MEA technology presented the lowest score in all scenarios, which indicates that it is the least economically viable technology compared to the alternatives. Oxyfuel and CaL technologies are ranked similarly in this category as they present comparable NPV, IRR, payback period and total costs in each scenario. These technologies may be economically competitive compared to Reference but only within the best-case scenario parameters (question 1). Still, no significant economic advantage was found compared to Reference. To overcome this gap, there might be the need for public funding to decrease the $CO_2$ capture CAPEX covered by private companies for the first CCUS projects. CaL and oxyfuel technologies present a higher CAPEX but a lower OPEX. As such, their total cost could decrease enough to be competitive with Reference if part of the CAPEX was obtained with public funding.

Energy and environmental KPIs show that, both in the intermediate and best-case scenarios, Reference presents the worst score compared to the alternatives, as expected. The highest score (0.33) is obtained for CaL for the three scenarios. This occurs due to its highest net $CO_2$ avoided, lowest net $CO_2$ emissions and net $CO_2$ Avoided Cost, although it presents a higher SPEC compared to Reference and oxyfuel. Depending on the scenario, oxyfuel has the second or third highest score, although significantly lower than CaL, while the MEA technology comes in third or fourth (question 2).

Technical KPIs, which are not scenario-dependent, suggest that MEA and CaL post-combustion technologies are assessed as easier to retrofit than integrated oxyfuel technology (question 3). The clear advantages of post combustion technologies are the low impact on the plant operability and clinker quality and the flexibility in placing new equipment in the cement plant. The highest score was obviously obtained for Reference (0.33), followed by MEA (0.30) and CaL (0.29). The oxyfuel technology, which is more integrated with the cement plant, is assessed as more challenging, with the lowest score (0.12).

Interestingly, the overall ranking among $CO_2$ capture technologies is essentially the same, regardless of the scenario. CaL has the highest score, followed by either oxyfuel or MEA, which show similar results (with a difference inferior to 9 %). Still, their order relative to Reference depends on the scenario. In the worst scenario, Reference presents the highest overall score while in the intermediate and best scenarios, CaL has the highest score compared to the alternatives. In the best scenario, all the technologies present a higher overall ranking compared to Reference.

In conclusion, from an economical perspective, both CaL and oxyfuel technologies show a better performance than MEA. However, CaL presents a higher environmental performance, and it is easier to retrofit than the oxyfuel technology. Overall, between the technologies analysed, the CaL technology is recommended to implement in the Portuguese cement plants (question 4). However, its advantage compared to Reference depends strongly on the scenario.

## 4. Conclusion

The cement industry faces the challenge of meeting an increasing demand for its product while cutting direct $CO_2$ emissions from its production. This paper developed a methodological framework, integrating a multi-criteria assessment and a Weighted Sum Model (with economic, energy/environment and technical considerations), and demonstrated its use in a case study to select the best technology to implement in a Portuguese cement plant considering three different scenarios.

Four $CO_2$ capture options in the Portuguese cement industry were compared: a reference Portuguese cement plant and three $CO_2$ capture technologies (MEA and CaL post-combustion and oxyfuel). A weighted matrix was developed, comprising 12 indicators grouped into the 3 performance criteria. The AHP method was used to determine the weights of each indicator by using pairwise comparison judgments.

The economic viability of the oxyfuel and CaL technologies was found to be similar, as they present comparable NPV, IRR, payback period and total costs in each scenario. On the other hand, MEA technology presented the lowest economic score in all the scenarios, which makes it the least economically viable technology analysed. Nevertheless, CaL and oxyfuel technology were only viable within the best-case scenario parameters. Still, no significant economic advantage was found compared to the Reference (plant without $CO_2$ capture technologies). To overcome this problem, there is a need for public funding to decrease the $CO_2$ capture CAPEX covered by private companies for the first CCUS projects (question 1).

Energy and environmental KPIs show that CaL presents the best performance, followed by oxyfuel. This is explained by the higher Net $CO_2$ Avoided to CaL (97 %), followed by oxyfuel (79 %) and MEA (57 %), an inversely lower net $CO_2$ emissions and Net $CO_2$ Avoided Costs. Still, the lowest SPECCA is obtained for oxyfuel (2.13 GJ/$t_{CO2}$), followed by CaL (4.86 GJ/$t_{CO2}$) and MEA (10.05 GJ/$t_{CO2}$). In both cases, the MEA shows the worst results (question 2). Technical KPIs indicate that MEA and CaL post-combustion technologies are easier to retrofit than the integrated oxyfuel technology (question 3).

In conclusion, overall, the use of the methodological framework was validated as an adequate strategy to support decision-making in $CO_2$ capture technologies, as it allowed to recommend the CaL technology, based on the case study of Portuguese cement plants. It became clear that its advantage compared to Reference depends strongly on the scenario (question 4).

Further studies should be conducted to determine the economic viability of the CaL technology considering public funding. Additionally, a further analysis that is not limited to the cradle-to-gate boundaries imposed in the paper herein could provide additional information regarding the techno-economic and environmental impact when considering the storage or use of the captured $CO_2$. Furthermore, a comparison between the cement plants should be performed to analyse the viability of capturing the $CO_2$ taking into account the specificities of each plant.

## CRediT authorship contribution statement

M. Bacatelo: Conceptualization, Methodology / Study design, Formal analysis, Investigation, Writing – original draft, Writing – review and editing, F. Capucha: Investigation, P.Ferrão: Writing – review and editing, F.Margarido: Writing – review and editing.

## 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.

## Data Availability

Data will be made available on request.

## Acknowledgements

This research was funded by the IST-ID (UIDP/50009/2020- FCT and UIDB/50009/2020- FCT) and c$^5$Lab - Sustainable Construction Materials Association (CENTRO-04-3559-FSE-000096 and LISBOA-05-3559-

FSE-000008). The authors gratefully acknowledge the contribution of ATIC (Associação Técnica da Indústria de Cimento) for providing the necessary data to establish the reference scenario. Special thanks to Susana Ribeiro (Secil), António Mesquita (Cimpor) and Paulo Rocha (Cimpor) for their help and support.

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jcou.2022.102375.

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