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Comparative techno-economic analysis of the integration of MEA-based scrubbing and silica PEI adsorbent-based CO_2 capture processes into cement plants

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ABSTRACT

The objective of this work was to perform the techno-economic analysis for the integration of two post-combustion carbon capture technologies into cement plants, namely monoethanolamine (MEA) scrubbing-based and silica-alkoxylated polyethyleneimine (SPEI) adsorbent-based processes. The key performance indicators were investigated, including emission abatement, energy performance, break-even selling price, CO_2 capture and avoidance cost. The technical evaluation showed that the conventional MEA and SPEI-based processes required 3.53 GJ/tonne CO_2 and 2.36 GJ/tonne CO_2 of regeneration energy when achieving 90% of CO_2 capture rate, respectively. In addition, the specific primary energy consumption for CO_2 avoided was estimated at 6.5 GJ/tonne CO_2 for the MEA-based and 4.3 GJ/tonne CO_2 for the SPEI-based process. The CO_2 capture costs of MEA and SPEI-based processes were estimated at 61.4 and 49.8 €/tonne CO_2, respectively. Meanwhile, the CO_2 avoidance cost of MEA and SPEI processes were estimated at 84.7 and 62.2 €/tonne CO_2 respectively. The economic evaluation indicated that the cost of clinker production was increased by 108% with the integration of the solvent-based MEA-based and 84% for the SPEI-based processes. However, in the case, the maximum heat of 53.9 MWth is recovered from the reference cement plant, the costs of CO_2 capture and CO_2 avoidance for both the MEA and SPEI-based processes would be reduced. The CO_2 capture costs of MEA and SPEI-based processes would decrease to 48.0 and 35.6 €/tonne CO_2, respectively. Additionally, the CO_2 avoidance costs for the MEA and SPEI-based processes would be reduced to 57.5 and 44.5 €/tonne CO_2, respectively.

1. Introduction

According to the Intergovernmental Panel on Climate Change report, carbon dioxide (CO_2) is the major contributor to greenhouse gas emissions. Among CO_2, methane, nitrous oxides, and fluorinated gases; CO_2 emissions account for more than 70% of the total global (EPA, 2019). Human activities are causing the accumulation of CO_2 in the atmosphere at a rate of 33 Gt CO_2 per year. Due to the high rate of CO_2 accumulation, the carbon cycle cannot hold this amount of CO_2 in natural sinks (Liu et al., 2022). If the current policies persist, the earth's surface temperature is expected to reach 1.5 °C between 2030 and 2052. In this scenario, it is a global consensus that immediate action is required to

minimise the level of CO_2 in the atmosphere (BP, 2022).

The industrial sector is responsible for more than a fifth of greenhouse gas emissions globally, and it is necessary to reduce CO_2 emissions significantly to achieve the global climate emission set forth by the Paris Agreement. In the industrial sector after iron, steel, chemicals, and petrochemicals, the third largest greenhouse contributor is the cement industry, accounting for approximately 7% of global CO_2 emissions (Ayub et al., 2021). Cement is used in manufacturing concrete, the main building material for buildings, bridges, pavements, etc. Therefore, cement production is expected to keep increasing because of infrastructure development and urbanisation (Izumi et al., 2021).

Typically, in a cement plant, approximately two-thirds of the CO_2

emissions arise from the calcination process of limestone when $CaCO_3$ is converted into CO_2 and CaO, while the remaining one-third of the emissions are linked to combustion of fuel in the kiln burner and calciner. Different routes have been reported to minimise CO_2 emissions from the cement industry i.e., utilisation of alternate renewable and sustainable fuel, employment of supplementary cementitious material (SCM) to replace clinker, and integration of carbon capture and storage (CCS) with existing cement plants (Ayub et al., 2021). However, the supply of alternate renewable and sustainable fuels and SCMs is limited compared to cement production (Gartner and Hirao, 2015). Furthermore, switching to alternate sustainable and renewable fuels can remove only one-third of the CO_2. While integrating a CCS process with the existing cement production process can reduce both the CO_2 emissions linked to the calcination process and fuel combustion. Therefore, integrating CCS technology is the only potential solution to reduce CO_2 emissions from the cement industry.

In the cement industry, CO_2 capture has been carried out using either oxyfuel combustion or a post-combustion carbon capture route. In the oxyfuel combustion route, pure oxygen is used instead of air for fuel combustion in the kiln and pre-calciner. The exhaust gases produced through this process mainly consist of water and approximately 90% CO_2. The produced CO_2 after the vapour separation is then compressed and liquified for transportation and storage (Cloete et al., 2019). The oxyfuel combustion process is a relatively new technology with low operating costs. But, it requires adaptation to the clinker production process, making it difficult to retrofit existing cement plants, since modifications in the design of the rotary kiln and pre-calciner are required (Hong, 2022).

Contrarily, post-combustion carbon capture technology is a mature technology with amine scrubbing has already been proven commercially (Olabi et al., 2022). This technology is considered advantageous because of its simple end-of-pipe configuration or retrofit ability for existing cement plants. Generally, the first-generation liquid amine-based absorbents are considered to capture CO_2 for commercial applications. However, there are certain disadvantages associated with amine scrubbing as it has high regeneration cost, potentially causes equipment corrosion, and it can undergo oxidative degradation and evaporation (Zhang et al., 2014). According to Yu et al. (2012) conventional amine-based absorbents have a lower absorption capacity compared to advanced amine sorbents. They reported that monoethanolamine has an absorption capacity of 0.5 mol/mol of absorbent, whereas aminoethylethanolamine, methyl diethanolamine, and diethylenetriamine have an absorption capacity of 1 mol/mol of absorbent. Recently, savings on the operational expenses has been achieved through the utilisation of advanced amine solvents however, it is important to consider that there is a corresponding increase in capital cost (Oh et al., 2020).

To overcome the barriers, research is being carried out on the development of second and third generation solid sorbent-based carbon capture technologies for their application in the post-combustion carbon capture processes, which is analysed in the present paper for cement production. The solid sorbents are advantageous as they have low regeneration heat requirement, less amine loss due to evaporation, and lower vessel corrosion potential. These sorbents can either be physical ones including activated carbon, zeolites, or chemical ones including alkaline-based sorbents, metal-organic framework and amine functionalised mesoporous silica (Ünveren et al., 2017).

The calcium looping post-combustion carbon capture process is an alternative method to capture CO_2 and has gained great attention due to its low CO_2 avoided cost and high heat recovery from the carbonation process, but requires high temperature conditions to operate, therefore, requires additional fuel to meet the energy demands (Rolfe et al., 2018). The heat recovered is utilised to generate electricity, however, a separate power plant is required which is not feasible for the scale of the process. Also, the integration of air separation unit is required in the case of direct heating calcium looping process which requires extensive energy and increase the capital and operating cost (De Lena et al., 2017).

Regarding post combustion carbon capture processes, amine-based solid sorbents have shown promising results for CO_2 capture. The amine functionalised mesoporous silica sorbents are stable and offers lower regeneration heat requirement compared to conventional amine scrubbing process (Yan et al., 2022). Furthermore, in comparison to the other solid sorbent, amine-based solid sorbents are considered as most advanced cost effective sorbents, with having higher adsorption and working capacity, mild regeneration energy, fast adsorption and desorption kinetics, and favourable operating temperature window (Zhang et al., 2017). For example, Sjostrom and Krutka. (2010) carried out the study to compare the regeneration temperature, working capacity and regeneration energy required of various solid sorbents. As shown in Table 1, the supported amine-based solid sorbents exhibit lower regeneration energy required and high working capacity compared to the carbon-based and zeolite-based solid sorbents. Advantages are likely to be gained using alkoxylated polyethyleneimines (PEIs) which are inherently more stable than normal PEI with respect to thermos-oxidative degradation with lower heats of adsorption meaning that both adsorption and desorption can be carried out at lower temperatures (Min et al., 2018).

Although considerable attention has been given to silica-based amine sorbents for the post-combustion capture, no work has been reported on novel silica alkoxylated PEIs potential application on a commercial scale in the cement industry, making it difficult to analyse its potential in the cement industry. This study aims to provide a techno-economic analysis of a novel alkoxylated SPEI sorbent-based technology for carbon capture in cement plants process and to compare it with conventional MEA-scrubbing. This study is based on real data from an existing cement plant and the SPEI-based capture process is simulated based on experimental and pilot-scale results provided by the University of Nottingham partner.

This work will interest cement manufacturers, who may require understanding the real cost and performance of cement plants with CCS retrofitted. Furthermore, policymakers would benefit from this work, as it could be used to benchmark CO_2 emissions and costs with CCS integration. Additionally, policymakers may use the results to better understand CCS and support the technical solution. Finally, academics can find key technical and cost data regarding the studied CCS solutions.

Table 1
Comparison of required regeneration temperature, working capacity and regeneration energy required of various solid sorbents.

Sorbent Type (ID)	Max. regeneration temperature (°C)	Working capacity (wt. %)	Regeneration energy (GJ/tonne CO_2)
Carbon nano tubes(A)	130	4.10	1.7
Carbon-based (B)	120	0.48	13.6
Carbon-based (C)	120	0.47	13.9
Supported amine(D)	120	7.01	2.6
Supported amine(E)	90	0.95	6.1
Supported amine(F)	120	4.23	3.4
Carbon-based (G)	120	0.38	17.2
Carbon-based (H)	120	0.75	8.7
Zeolites-13x (J)	250	0.80	18.8
Zeolites-5A (M)	250	1.28	12.2
Zeolite-HiSiv 3000(N)	150	0.37	26.4
Zeolite-NaY (O)	250	1.12	13.3

2. Methodology

2.1. Modelling and boundary conditions

In this study, the integration of the two post-combustion CO_2 capture technologies, i.e., MEA and SPEI-based processes, into the cement plant are investigated for CO_2 reduction. For evaluating their technical and economic performance, the following scenarios are considered:

Scenario 1: Reference cement plant without carbon capture.

Scenario 2: The cement plant integrated with the MEA-based carbon capture process.

Scenario 3: The cement plant integrated with the SPEI-based carbon capture process.

The ECLIPSE process simulator, which is a personal computer-based package with built-in programs for mass and energy balance and capital cost estimation is used to carry out the simulation and modelling of all the case scenarios. The logical stage flowchart for the techno-economic analysis is shown in Fig. 1. The first stage of the simulation modelling involves the development of a process flow diagram; at this stage, streams are also specified. After stream specification and the input of the process parameters, the mass and energy balances are generated. This involves an enthalpy calculation of each stream. In the third stage, the energy consumed by each utility is calculated in the ECLIPSE utility package.

2.1.1. Feedstock composition

The meal used for clinker production contains limestone, clay, sand, and iron. The percentage of limestone, clay, sand, and iron in the raw meal is estimated at 77.7 wt%, 18.6 wt%, 2.3 wt%, and 1.4 wt% respectively. In addition, the moisture content in each component is also identified. The moisture content in limestone, clay, sand, and iron is estimated at 15.2 wt%, 14.0 wt%, 22.1 wt%, and 5.3 wt%, respectively.

In the reference cement plant, coal is combusted in the burner. While in the pre-calcination process, coal, refused derived fuel (RDF) and waste tyres are used as fuel. The ultimate analysis of coal, RDF, and waste tyres, on an as-received basis, is presented in Table 2.

2.1.2. Indirect heat consumption and CO_2 emissions

Indirect heat consumption refers to the primary energy consumed in relation to the net electricity consumption during the cement production process. To calculate the indirect heat consumption, the reference plant should be defined. It is assumed that the required electricity is provided by the national grid having an electricity production efficiency of 62% and an average carbon emissions rate of 274 kg CO_2/MWh in the UK (BP, 2022).

Table 2
Main characteristics of fuels.

	Coal	RDF	Tyres
Hydrogen (Wt.%)	5.0	7.2	8
Carbon (Wt.%)	65.7	53.0	52.1
Sulphur (Wt.%)	0.5	0.3	2
Oxygen (Wt.%)	11.8	0	8
Nitrogen (Wt.%)	1.7	1.4	0
Water (Wt.%)	2	23.7	15
Ash (Wt.%)	13.3	14.4	0
LHV (MJ/kg fuel)	26.0	18.8	25.9

For natural gas consumption, it is assumed that a gas boiler provides heat with an efficiency of 90% and a carbon emission rate of 56.1 kg CO_2/GJ NG. Thus, these carbon emission rate factors are considered to calculate the indirect CO_2 emissions from electricity and from natural gas (Voldsund et al., 2019).

2.1.3. Scenario 1- reference cement plant operating conditions

Scenario 1 presents the reference cement plant without integrating a carbon capture process. The process of cement production involves processing the mineral raw material in a specific ratio for clinker formation with specific chemical and physical properties. The schematic diagram for the clinker formation process is shown in Fig. 2.

We developed a reference cement plant simulation model based on the data provided by our industrial partner, CEMEX. Based on the obtained data, the boundary conditions were defined, and mass and energy balance were evaluated. The plant data included raw meal chemical composition, raw mix proportions, and process information such as fuel composition, heat demand, clinker production, raw meal consumption, flue gases, emissions, etc. for a 3200-tonnes/day clinker plant. Fig. 3 shows the information related to the main operating parameters of the CEMEX cement plant. The clinker production process involves a wide range of reactions Table 3. As given, the CEMEX cement plant consists of four preheating stages, with the first stage consisting of twin cyclones. The raw meal enters the preheaters and is heated to 880 °C by the flue gas produced from the kiln burner and calciner. The preheaters temperatures are at 370, 563, 737 and 880 °C for the first, second, third and fourth stage preheaters. It is assumed that an ideal solid-gas separation takes place in the cyclone preheaters to reduce the complexity of process modelling. The temperature of the flue gas stream leaving the preheaters and entering the raw meal mill is 325 °C. Also, the portion of the hot gas stream from preheaters is fed into the coal mill at the temperature of 325 °C. The raw meal from the preheaters enters the pre-calciner for the calcination process by producing CO_2 and CaO Eq. (1). After calcination at 900 °C, the calcined meal finally enters into the kiln burner where the
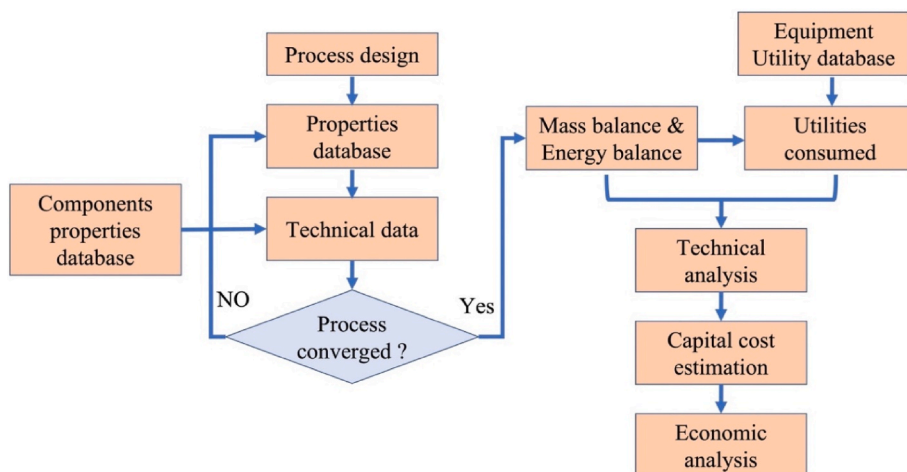

Fig. 1. Logical flow chart for eclipse process modelling and simulation process.
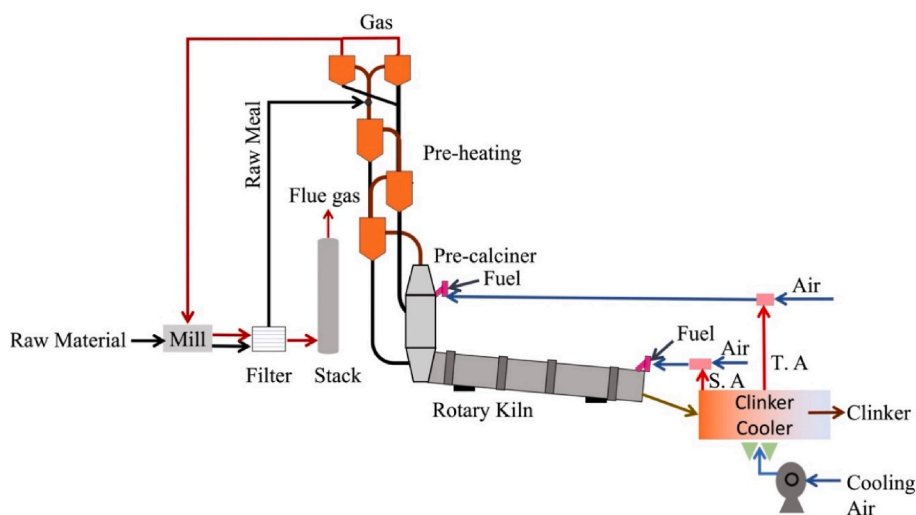
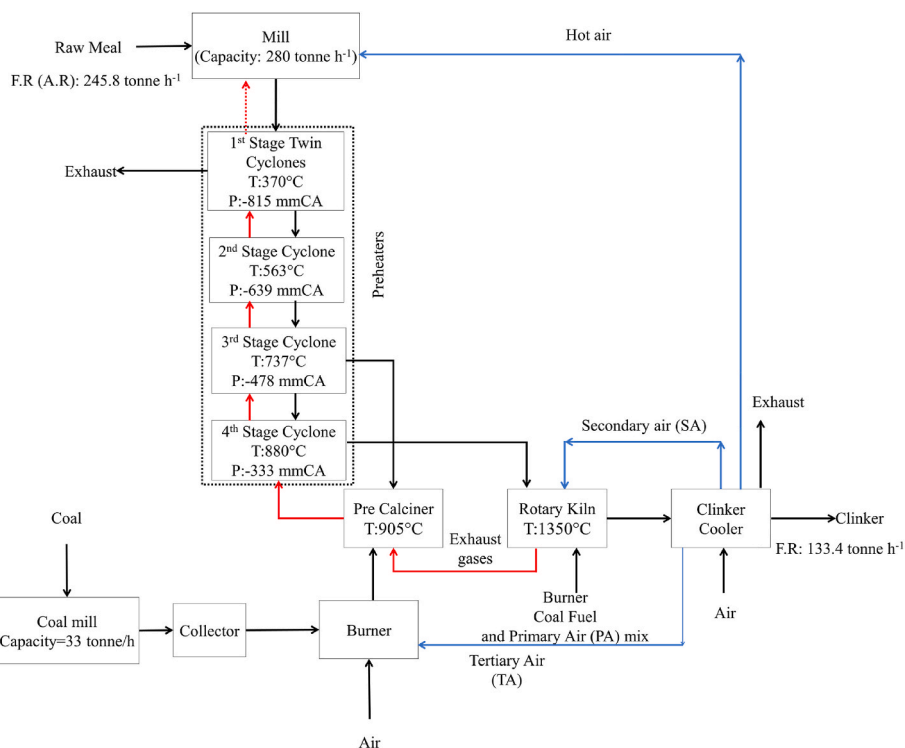**Fig. 2.** Schematic diagram of reference cement plant.

Fig. 3. Main operating parameters of the reference cement plant.

series of reactions takes place at 1350 °C that leads to clinker production Eq. (2) to Eq. (6).

Ambient air is used to cool the clinker, and the hot air produced is split into three preheating streams. The secondary air from the clinker cooler is added to the rotary kiln burner at the temperature of 1000 °C. While the tertiary air from the clinker cooler is fed into the pre-calciner at the temperature of 973 °C. In addition, the hot air stream produced from the clinker cooler at a temperature of 213 °C is fed into the raw meal mill to achieve the desired temperature at the inlet.

2.1.4. Scenario 2- MEA-based carbon capture process operating conditions

Scenario 2 integrates the MEA-based capture process with the reference cement plant. This process can be integrated away from the kiln and no design modifications are required; therefore, its retrofit

ability is advantageous. The MEA-based carbon capture process involves a series of steps to capture CO_2 from the flue gas produced by the cement plant. As shown in Fig. 4, MEA is a single-unit system that captures the CO_2 from the flue gas produced by the cement plant.

To simulate the MEA-based carbon capture process, we assume that the flue gas, containing 150 tonnes/hr of CO_2 produced by the cement plant and natural gas boiler, is initially cooled to 40 °C to remove water. The cooled flue gas then enters the absorber, which typically operates at a temperature of ~40 °C. In the absorber column, the aqueous MEA 30 wt% solution captures 90 wt% of CO_2 from the flue gas. Main operating parameters of the MEA-based carbon capture system are the sorbent/ CO_2 ratio, which influences the CO_2 capture rate and regeneration energy. For the study, the MEA/CO_2 mass ratio is assumed at 2.8. The CO_2 uptake in the absorber is assumed at 0.45 mol CO_2/mol MEA (Abu-Zahra

Table 3
Reactions involved in clinker production.

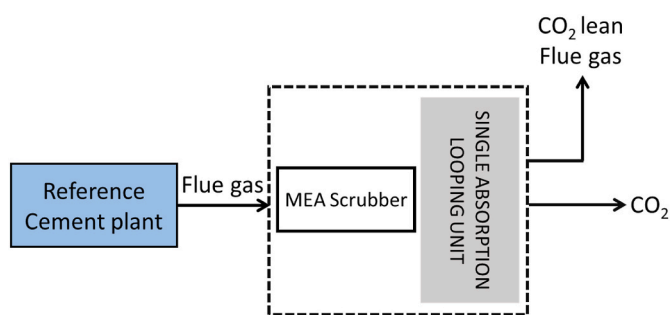| Reactions	Equation
Calcination Reaction (Pre-calciner step)	
$CaCO_3 \rightarrow CaO + CO_2$	Eq. (1)
Clinker Formation Reaction (Rotary kiln step)	
$2CaO + SiO_2 \rightarrow Ca_2SiO_4$	Eq. (2)
Dicalcium silicate	
$3CaO + SiO_2 \rightarrow Ca_3SiO_5$	Eq. (3)
Tricalcium silicate	
$3CaO + Al_2O_3 \rightarrow Ca_3Al_2O_6$	Eq. (4)
Tricalcium aluminate	
$Al_2O_3 + 4SiO_2 + H_2O \rightarrow Al_2Si_4O_{10}(OH)_2$	Eq. (5)
Pyrophyllite	
$Al_2O_3 + 2SiO_2 + H_2O \rightarrow Al_2.Si_2O_5(OH)_4$	Eq. (6)
Kaolinite	

Fig. 4. Schematic diagram of MEA-based carbon capture process integration.

et al., 2007).

The CO$_2$-rich MEA solvent then enters the desorption column at ~150 °C where the MEA solvent is regenerated (Zhang et al., 2017). The heat for the regeneration is provided by the reboiler operating at 130 °C (Ying et al., 2019). The output stream of the desorption reactor is cooled to 90 °C to condense and separates 90% of MEA and MEA-CO$_2$. The recovered stream (lean and rich MEA solvent) splits into two streams. The small portion of the separated stream (~10 wt%) is recycled back into the desorption column after passing through the reboiler. Once the stream has been purged at a rate of 3.2 kg sorbent/tonne of CO$_2$, and heat exchanged in the heat exchanger, most of the separated stream (~90%) is recycled back into the absorption column. In the heat exchanger, the CO$_2$ lean MEA solution and the CO$_2$ rich MEA solution flow in a counter-current pattern and exchange heat. The amine lean solvent loading is assumed at 0.23 mol CO$_2$/mol MEA (Abu-Zahra et al., 2007). The process flow configuration of the MEA process is shown in Fig. 5.

2.1.5. Scenario 3- SPEI-based carbon capture process operating conditions

The SPEI-based carbon capture process integrated with the reference cement plant is studied in Scenario 3. As depicted in Fig. 6, the SPEI solid sorbent scrubber is a modular carbon capture technology that uses a solid sorbent material to capture CO$_2$ from the flue gas produced by cement plants. Unlike the MEA-based process, the SPEI operates as a modular unit due to the maximum bed diameter used for fluidized beds, with multiple units required to capture CO$_2$ produced by the cement plant. Based on our calculation, four parallel units are required to capture CO$_2$ from the cement plant.

For the simulation modelling of a SPEI-based capture process, the SPEI sorbent used is composed of 47% PEI and 53% silica. The flue gas, which contains 141 tonnes per hour of CO$_2$ produced from the reference cement plant and natural gas boiler, splits into 4 parallel streams. The flue gas in each module is initially cooled at 50 °C to reduce the moisture content to a maximum of 10%. The flue gas then enters the bubbling bed sorption reactor, and the CO$_2$ is adsorbed at ~50 °C using the solid alkoxylated PEI sorbent. Circulating or bubbling-beds can be used. However, circulating beds have shorter residence times, which means that a higher amount of CO$_2$ in the flue gas is not captured. Therefore to
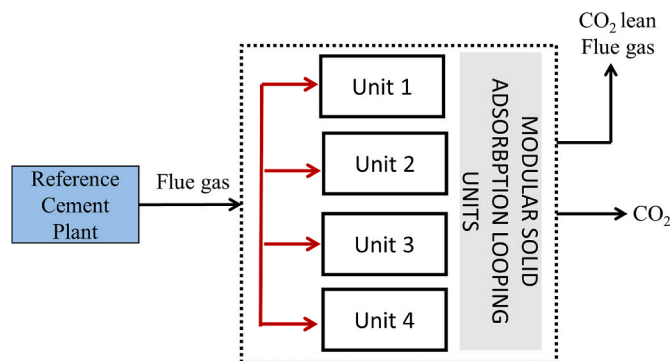

Fig. 6. Schematic diagram of SPEI-based carbon capture process integration.
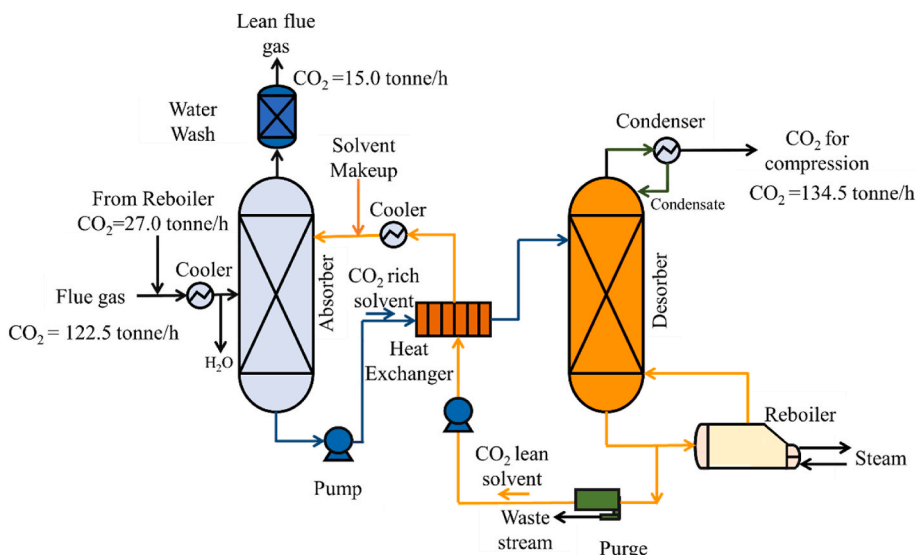

Fig. 5. Process flow diagram of MEA-based carbon capture process.

achieve 90% of CO_2 capture efficiency a high loading capacity (i.e., mol of adsorbent/mol CO_2 absorbed) is required. Since the sorbent/CO_2 ratio and residence times significantly affect the carbon capture rate and the regeneration of sorbent, therefore, the optimised sorbent/CO_2 mass ratio of 10 is considered for the simulation of bubbling fluidized bed reactor. As the process uses a bubbling fluidized bed reactor, a higher residence time is required. At 90% capture rate, the CO_2 uptake in the adsorber is calculated at 2.05 mmol/g.

After adsorption, the CO_2-rich sorbent is conveyed to the bubbling bed desorber, where close to 100% CO_2 is desorbed thermally from the sorbent in the desorber at 110–120 °C, and the sorbent is regenerated. The temperature is dependent on the CO_2 partial pressure in the desorber. The external heat is provided to achieve the desired temperature in the desorber provided. After desorption, the lean SPEI sorbent stream is recycled back into the adsorption reactor after purging the recycle stream at 0.1% and cooling at the temperature of 50 °C (Zhang et al., 2014). Finally, 50% of the desorbed CO_2 is recycled back into the desorption reactor. The CO_2 working capacity of SPEI is assumed at 1.25 mmol/g of sorbent with dynamic sorption capacity at 5.5 wt%. The working capacity obtained from experiments is comparable to other supported-amine-based sorbents reported by Sjostrom and Krutka. (2010) in Table 1. The process flow configuration of the SPEI carbon capture process is shown in Fig. 7.

2.1.6. CO_2 compression and liquefaction

In the liquefaction process, the captured CO_2 is initially dried and compressed to achieve the final pressure of 110 bar. The liquefaction process involves the compression of gaseous CO_2 through a four-stage process. The CO_2 gas is cooled to a temperature of 25 °C before entering each stage of the compressor, having an adiabatic efficiency of 85%. Each intercooler is followed by flash separators which separate the

liquid CO_2 with high purity at low temperatures. Through this approach, the CO_2 product stream reaches a purity level of 96% which is suitable for the CO_2 sequestration application (Brownsort, 2019). The CO_2 liquefaction process is common for the MEA-based and SPEI-based carbon capture processes.

2.1.7. Economic modelling assumptions

The economic analysis of all the case studies scenarios is performed for two purposes *i)* to identify the capital and operating costs *ii)* to calculate the break-even selling price (BESP). The mass and energy balance obtained by performing the technical analysis through the ECLIPSE process simulator provides the design basis to calculate the capital cost of each equipment. The capital cost estimation of each equipment is carried out using two approaches. If the equipment is of standard size, then literature review, manufacturer quotes, and published literature is used. If the capital cost of a similar component with different size is known, then the capital cost is scaled to the required size using the following correlation:

$$Cost_2 = Cost_1 \left[\frac{Size_1}{Size_2} \right]^{scaling\ factor} \qquad \text{Eq. (7)}$$

Where $Cost_1$ and $Cost_2$ are the reference cost of equipment having capacity $Size_1$ and $Size_2$ respectively. While the value of the scaling factor ranges from 0.55 to 0.75.

If the equipment is not standard equipment, then a seamless estimation of cost is performed using the ECLIPSE process simulator. This calculation is also based on the data generated through mass and energy balance. However, other co-relation factors are considered including operating conditions and material of construction. In addition, an allowance is also given for the installation cost. While all possible efforts
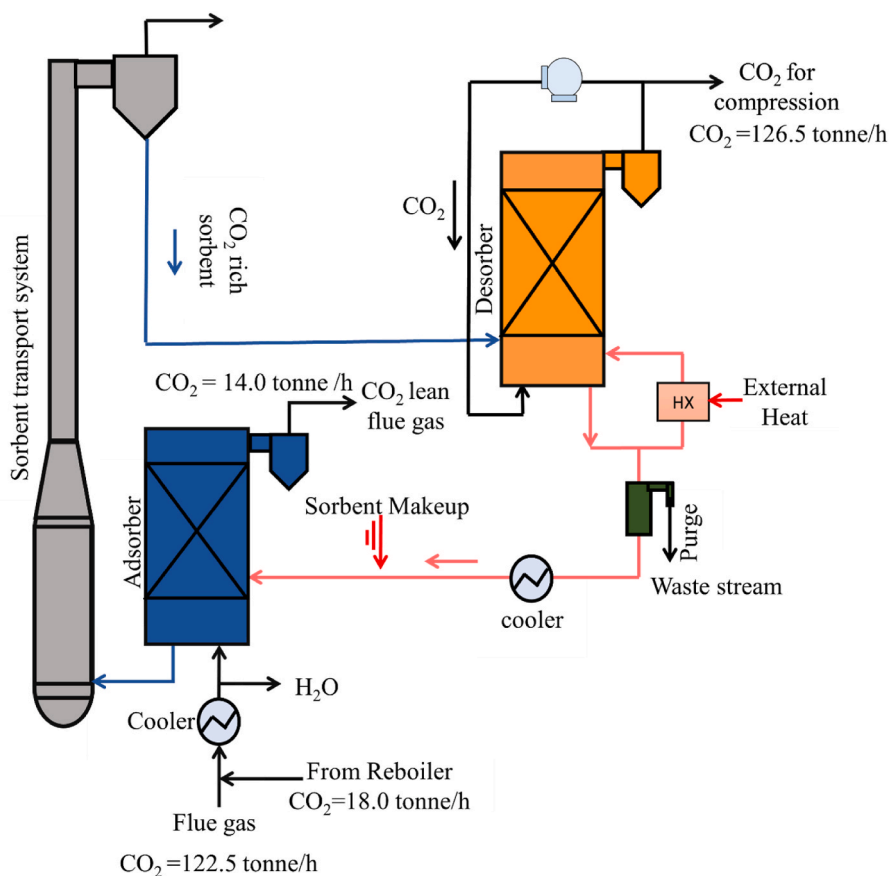

Fig. 7. Process flow diagram of SPEI-based carbon capture process.

are made to validate the capital cost of equipment, the absolute accuracy of all the equipment is estimated at 25–30%.

Once the capital cost of the equipment is estimated, the analysis of the impact of the integration of various carbon capture processes on the CO_2 capture cost and CO_2 avoidance cost is calculated. To calculate these values, the BESP of each scenario should be calculated using the ECLIPSE process simulation software. This simulation software package is used to estimate capital investment along with variable and fixed operating and maintenance costs. The key economic factors and indices that must be defined to obtain accurate economic analysis are presented in Table 4.

3. Results and discussion

3.1. Technical analysis

3.1.1. Scenario 1- the reference cement plant

Based on the experimental data, the base case cement plant with a clinker production capacity of 133.4 tonne/hr is modelled. The total thermal input required for clinker production is 133.4 MW, corresponding to the required specific direct heat at 3.60 GJ/tonne clinker, which is the ratio of total thermal input to total clinker produced. 60% of the total thermal energy is utilised for the calcination process, while the remaining 40% of the total thermal energy is utilised in the kiln burner. The total specific direct heat consumption for the calcination process is estimated at 2.16 GJ/tonne clinker, and 1.44 GJ/tonne clinker produced for the kiln burner. In addition, the electricity consumption for the raw meal preparation, kiln operation, clinker grinding, and cooling is calculated at 16.3 MWe, corresponding to 0.12 MWh/tonne clinker.

The concentration of flue gas leaving the reference cement plant contains; CO_2 at 16.5 vol%, N_2 at 58.2 vol%, O_2 at 6.8 vol %, argon at 0.39 vol% and H_2O at 18.1 vol%. The emission rate of CO_2 from the reference cement plant is estimated at 123 tonne CO_2/hr which corresponds to 0.92 tonne CO_2/tonne clinker. The simulation results showed that the 64 wt% of the direct CO_2 emissions are from the calcination process through the decomposition of $CaCO_3$ into CO_2 and CaO. The remaining CO_2 is produced by burning fuels in the kiln burner. If 0.27 tonne CO_2/MWh of CO_2 emission factor for electricity generation is considered, the indirect CO_2 emissions showed the equivalent CO_2 emissions at 0.95 tonne CO_2/tonne clinker. The detailed technical results with energy performance indicators are given in Table 5.

3.1.2. Scenario 2- integration of the MEA-based carbon capture process into the cement plant

In the MEA configuration, the cement plant integrated with MEA-based carbon capture process can reduce CO_2 emission to 90% from

Table 4
Economic factors and indices to calculate CO_2 capture and CO_2 avoidance cost.

Economic factors	Baseline
Project life (years)	25
Plant operating hours/year	8000
Discount cash flow rate (%)	6
Owner Cost (%.EPC)	10
Contingencies (%.TCI)	10
Maintenance cost (%.TCI)	4
Insurance cost (%.TCI)	1.5
Raw meal (€/tonne)	4
RDF cost (€/tonne)	−75
Coal cost (€/tonne)	51.4
Waste tyres cost (€/tonne)	−153
MEA makeup (€/tonne)	1600
SPEI (€/tonne)	6500
Electricity price (€/MWh)	115
Natural gas price (€/MWh)	25
Fresh water price (€/tonne)	2

Table 5
Technical results of reference cement plant.

Main process data	Value
Raw meal input (tonne/hr, dry basis)	208.9
RDF input (tonne/hr, as received)	14.0
Tyres input (tonne/hr, as received)	1.4
Coal input (tonne/hr, as received)	7.0
Total thermal input (MWth)	133.4
Clinker production (tonne/hr)	133.4
Raw meal/clinker ratio (dry basis)	1.57
Power consumption (MWe)	16.3
Specific power consumed (MWh/tonne Clinker)	0.12
Specific direct heat required (GJ/tonne Clinker)	3.60
Specific indirect heat required (GJ/tonne Clinker)	0.71
Equivalent specific heat required (GJ/tonne Clinker)	4.31
CO_2 emissions on-site (tonne CO_2/hr)	122.5
Specific direct CO_2 emission (kg CO_2/tonne Clinker)	919
Indirect CO_2 emission (kg CO_2/tonne Clinker)	34
CO_2 emissions (kg CO_2/tonne Clinker)	952

the flue gas. The raw material input is kept constant to compare it with the reference cement plant. It can be shown from the simulation results, the clinker production rate is at 133.4 tonne/hr. The total direct thermal energy required for the process is at 133.4 MWth. It is assumed that the regeneration heat for sorbent regeneration is provided by natural gas and the CO_2 produced by burning natural gas in the boiler needs to be captured. Therefore, two streams of CO_2 are captured i) CO_2 produced from the cement plant and ii) CO_2 produced from the natural gas boiler. The CO_2 flow rate at the inlet of MEA-based carbon capture process is at 149.5 tonne/hr; out of which 82% is contributed by the reference cement plant and the remaining 18% is contributed by the natural gas boiler.

Considering the cement plant, MEA carbon capture process and the CO_2 compression and liquefaction unit, the electricity consumption is estimated at 31.0 MWe, corresponding to 0.23 MW/tonne clinker. In addition, the simulation results showed that the steam reboiler requires 162.8 MW of regeneration heat, corresponding to 3.53 GJ/tonne CO_2. These results are in agreement with the results reported in previous study by Markewitz et al. (2019).

The total CO_2 captured (inc. CO_2 from the natural gas boiler) by integrating the MEA-based carbon capture process with the cement plant is 134.5 tonne/hr. The specific direct heat required is at 3.60 GJ/tonne clinker, the indirect heat required is 1.35 GJ/tonne clinker and the specific heat required by the natural gas boiler is at 4.39 GJ/tonne clinker. Also, the imported electricity gives positive equivalent CO_2 emissions at 23.5 tonne/hr corresponding to 0.18 tonne CO_2/tonne of clinker produced. The total equivalent CO_2 avoided, and specific primary energy for CO_2 avoided (SPECCA (De Lena et al., 2019)) is estimated at 0.78 tonne CO_2/tonne of clinker and 6.5 GJ/tonne CO_2. These results are in agreement with the results reported in the literature by Voldsund et al. (2019). The detailed technical results with energy performance indicators of the MEA-based carbon capture process integrated with the cement plant are presented in Table 6.

3.1.3. Scenario 3- integration of SPEI-based carbon capture process into the cement plant

With the SPEI-based carbon capture process integration, the reference cement plant can reduce the CO_2 emission to up to 90% from the flue gas. The raw meal feeding rate is kept constant i.e., the raw meal at 208.9 tonne/hr leads to the clinker production at a rate of 133.4 tonne/hr. The total direct thermal input required is 133.4 MWth with having specific direct heat consumption of 3.60 GJ/tonne clinker. To compare with the MEA-based carbon capture process, in the SPEI-based carbon capture process it is also assumed that sorbent regeneration heat is provided by natural gas and the CO_2 emitted is captured. Therefore, in the case of the SPEI-based carbon capture process, the CO_2 flow rate at the inlet is at 140.6 tonne/hr; with 87% contribution from the reference

Table 6
Technical results of MEA-based carbon capture process integration.

Main process data	Values
Raw meal input (tonne/hr, dry basis)	208.9
Thermal input for the reference plant (MWth)	133.4
Energy supply for MEA regeneration (MWth)	162.8
Required regeneration energy (GJ/tonne CO_2)	3.53
Clinker production (tonne/hr)	133.4
Total power consumption (MWe)	31.0
Specific power consumed (MWh/tonne Clinker)	0.23
Equivalent specific energy required (GJ/tonne Clinker)	9.34
CO_2 captured (tonne CO_2/hr)	134.5
CO_2 emissions on-site (tonne CO_2/hr)	15.0
CO_2 capture rate (%)	90
Specific direct CO_2 emission (kg CO_2/tonne Clinker)	112.1
Specific indirect CO_2 emission (kg CO_2/tonne Clinker)	63.7
Equivalent specific CO_2 emissions (kg CO_2/tonne Clinker)	175.8
Equivalent CO_2 emissions avoided (kg CO_2/tonne Clinker)	776.4
SPECCA (GJ/tonne CO_2)	6.5

cement plant and 13% contributed by the natural gas boiler.

Considering electricity consumption in the reference cement plant, SPEI-based carbon capture process, and CO_2 compression and lique-faction unit, the total electricity consumption is estimated at 29.8 MWe, corresponding to specific power consumption at 0.22 MW/tonne clinker. Focussing on the energy requirement in the reboiler for sorbent regeneration, the simulation result showed that the steam reboiler requires 102.4 MW of regeneration heat, corresponding to 2.36 GJ/tonne CO_2.

For the work presented in this paper, the CO_2 capture rate is calculated at 126.5 tonne CO_2/hr and the total CO_2 emission rate from the process is 14.0 tonne CO_2/hr. The SPEI-based carbon capture process has a lower CO_2 capture rate than the MEA-based process because it requires less external heat, resulting in fewer CO_2 emissions from the external source. Therefore, the CO_2 capture rate is reduced. To ensure fair comparison with the MEA-based carbon capture process, similar energy generation scenarios are studied i.e., 62% efficiency of electricity generation and 90% efficient natural gas boilers for steam generation. The specific direct heat, specific indirect heat, and required specific heat by natural gas boiler are calculated at 3.60, 1.30 and 2.80 GJ/tonne clinker respectively. The equivalent CO_2 emissions show a positive value at 22.2 tonne/hr, corresponding to 0.17 tonne CO_2/tonne clinker. The total equivalent CO_2 avoided and the SPECCA are calculated at 0.78 tonne CO_2/tonne of clinker and 4.3 GJ/tonne CO_2 respectively. The detailed technical results with the energy performance indicators of the SPEI-based carbon capture process integrated with the reference cement plant are presented in Table 7.

Table 7
Technical results of SPEI-based carbon capture integration.

Main process data	Value
Raw meal input (tonne/hr, dry basis)	208.9
Total thermal input for the reference plant (MWth)	133.4
Energy supply for SPEI regeneration (MWth)	101.4
Required regeneration energy (GJ/tonne CO_2)	2.36
Clinker production (tonne/hr)	133.4
Power consumption (MWe)	29.8
Specific power consumption (MWh/tonne Clinker)	0.22
Equivalent specific energy required (GJ/tonne Clinker)	7.66
CO_2 captured (tonne CO_2/hr)	126.5
CO_2 emitted on-site (tonne CO_2/hr)	14.1
CO_2 capture rate (%)	90
Specific direct CO_2 emissions (kg CO_2/tonne Clinker)	108.2
Specific indirect CO_2 emissions (kg CO_2/tonne Clinker)	61.2
Equivalent specific CO_2 emissions (kg CO_2/tonne Clinker)	169.4
Equivalent CO_2 emissions avoided (kg CO_2/tonne Clinker)	782.9
SPECCA (GJ/tonne CO_2)	4.3

3.2. Economic analysis

3.2.1. Comparison of key performance indicators

The detailed results of the economic analysis including the capital and operating costs are listed in Table 8. To perform the comparison between key performance indicators (KPIs) it is assumed that the heat for the sorbent regeneration is provided by a natural gas fired boiler. Based on mass and energy balance results, the installed cost of the reference cement plant is estimated at 214.7 M€. Considering capital fees, working capital, commissioning cost and loan repayment, the total project investment increases to 268.35 M€. The total operating cost of the process is estimated at 15.9 M€/year. This gives a BESP of 57.1 €/tonne clinker.

In the MEA-based carbon capture process, the installed cost is estimated at 52.1 M€. The integration of the CO_2 compression unit increases the cost to 68.5 M€. Therefore, the total installed cost of the cement plant with CO_2 capture and compression processes is estimated at 283.2 M€. Including the capital fees, working capital, commissioning cost and loan payment increases the cost to 354.0 M€. The annual operating and maintenance costs are 69.2 M€. For the plant to have a zero NPV, a BESP of 119.0 €/tonne clinker is required.

For the SPEI-based carbon capture process the total capital cost is estimated at 38.6 M€. The integration of the CO_2 compression unit increases the capital cost to 54.3 M€. The total installed capital cost of the integrated cement plant with the SPEI system is estimated at 269 M€. Including the capital fees, working capital, commissioning cost and the loan repayment, the total project investment increases to 336 M€. The total operating and maintenance costs of the plant are estimated at 56.2 M€/year, resulting in a BESP of 104.9 €/tonne clinker.

Compared to the equipment costs of the SPEI, the MEA-based carbon capture process is around 25% more expensive. There are several reasons linked to the higher cost of the MEA-based carbon capture process. First, the capital cost of the MEA process is mainly influenced by the costs of absorber and desorber reactors, heat exchangers, and pumps because MEA solutions are corrosive, resulting in high costs associated with materials. Second, regenerating CO_2-rich solutions in the MEA stripper requires more energy than the SPEI bubbling bed, increasing the size of the reboiler. Furthermore, the mass flow rate of flue gases entering the MEA system is higher than that of flue gases entering the SPEI process. As a result, a bigger size of the MEA system is required to accommodate the volume of flue gas.

Fig. 8 presents the breakdown of operating costs, which shows that economic benefits can be obtained in all the case scenarios by using RDF (Rolfe et al., 2022) and waste tires (BLOG, Any Junk, 2020) as fuel in the reference cement plant while charging gate fees. The high operating cost of the MEA process is due to the higher sorbent regeneration energy

Table 8
Economic analysis results.

|	Reference plant	MEA-integration	SPEI-integration
Total equipment (EPC) cost inc. CO_2 capture and compression (M€)	214.7	283.2	268.9
Total capital cost (M€)	236.2	311.5	295.8
Total capital investment (M€)	268.4	354.0	336.1
Operating cost (M€/year)	15.9	69.2	56.2
BESP (€/tonne clinker)	57.1	119.0	104.3
Limestone (€/tonne clinker)	7.37	7.37	7.37
RDF (€/tonne clinker)	−7.89	−7.89	−7.89
Coal (€/tonne clinker)	2.69	2.69	2.69
Tires (€/tonne clinker)	−1.55	−1.55	−1.55
Electricity (€/tonne clinker)	14.06	26.75	25.68
Water (€/tonne clinker)	0.21	1.05	0.21
Natural gas (€/tonne clinker)	n/a	30.52	19.2
Sorbent Makeup (€/tonne clinker)	n/a	6	6.82
CO_2 avoidance cost (€/tonne CO_2)	n/a	84.7	62.2
CO_2 capture cost (€/tonne CO_2)	n/a	61.4	49.8
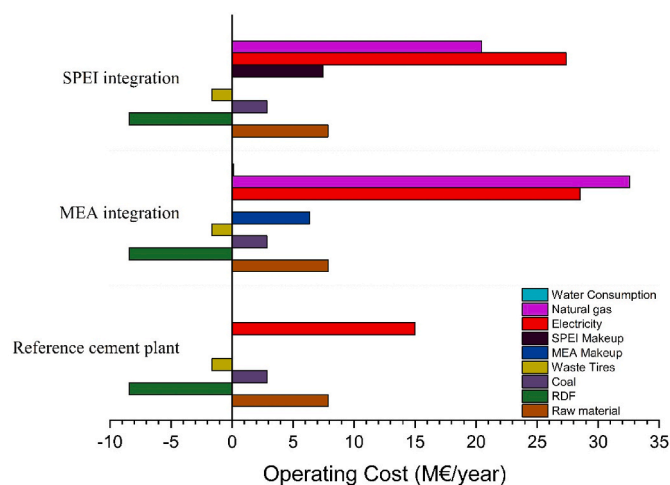
Fig. 8. Breakdown of operating costs.

requirement, compared with the SPEI-based carbon capture process. Although, the sorbent cost of SPEI process is higher compared to that of the MEA, but there are higher losses and greater degradation in MEA-based carbon capture process. At MEA costs of 1600 €/tonne and SPEI costs of 6500 €/tonne, the total replacement cost per year of the MEA solvent is calculated to be 6.4 M€, while the replacement cost for the SPEI sorbent is calculated to be 7.5 M€.

Based on the calculations presented in this work, the CO_2 capture cost (inc. compression) for MEA-based and silica-PEI-based carbon capture processes are calculated at 61.4 and 49.8 €/tonne CO_2, respectively. While the CO_2 avoidance cost (inc. compression) for MEA-based and SPEI-based carbon capture processes are calculated at 84.7 and 62.2 €/tonne CO_2, respectively. The capture cost for advanced amine processes is comparable to the SPEI-based process, being lower than MEA. The reported CO_2 capture cost of the advanced amine (MDEA) process is 54 €/tonne CO_2 and the CO_2 avoidance cost is estimated at 68 €/tonne CO_2 (Mostafavi et al., 2021), still about 9% higher than that of SPEI.

3.2.2. Sensitivity analysis

The KPI's of the cement plant and integrated processes reported in section 3.2.1 vary with the location of the plant. For this reason, to investigate the change in the KPI, the sensitivity analysis is performed by varying the following parameters.

1. Natural gas price: 20 to 30 €/MWh
2. Electricity price: 100 to 130 €/MWh
3. Carbon tax: 0 to 100 €/tonne CO_2

The sensitivity analysis of the CO_2 capture cost and CO_2 avoidance cost to the natural gas price and electricity price (based on prices before the COVID-19 pandemic) are presented in Figs. 9 and 10. Fig. 11 presents the sensitivity analysis for the clinker BESP in response to a carbon tax. The UK has implemented a carbon tax on carbon-intensive industries, with the tax increasing from 18 to €94 between 2019 and 2023 and is expected to continue increasing in the future.

As shown, the natural gas price significantly affects the CO_2 capture cost and CO_2 avoidance cost of the MEA-based and SPEI-based carbon capture processes integrated into cement plants. The CO_2 capture cost for the cement plant with the MEA-based carbon capture process varies from 55.4 to 67.5 €/tonne CO_2, and the CO_2 avoidance cost increases from 76.5 to 93.1 €/tonne CO_2 with the increase in natural gas price from 20 to 30 €/MWh.

Likewise, in the case of the cement plant with SPEI-based carbon capture process, the CO_2 capture cost and CO_2 avoidance cost increased from 45.7 to 53.8 €/tonne CO_2 and 57.1 to 67.3 €/tonne CO_2 respectively.
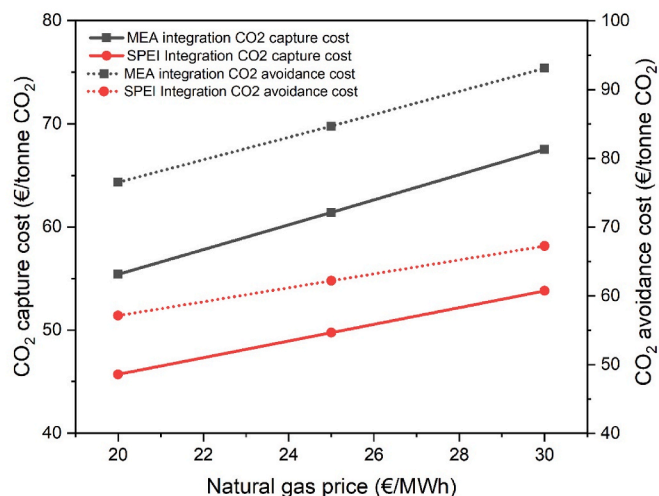

Fig. 9. Sensitivity analysis of CO_2 capture and CO_2 avoided costs to the natural gas price.
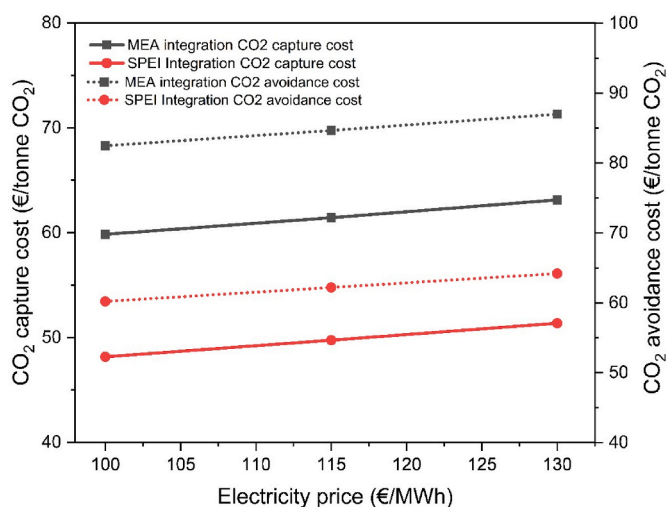

Fig. 10. Sensitivity analysis of CO_2 capture cost and CO_2 avoided to the electricity price.
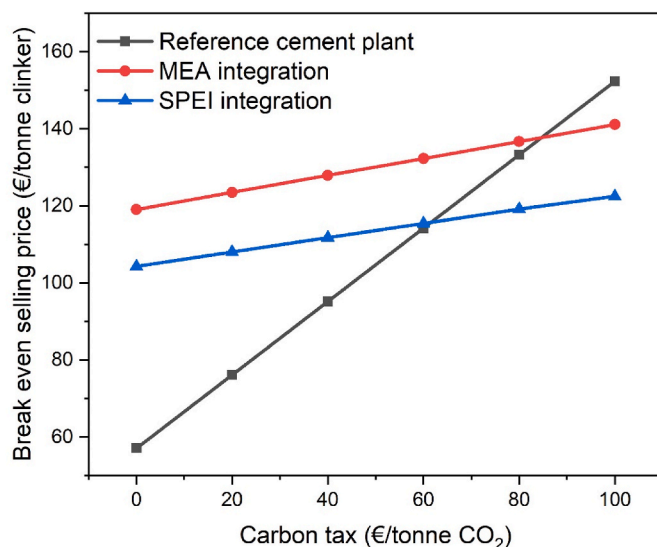

Fig. 11. Sensitivity analysis of BESP to the carbon tax.

Additionally, the CO_2 capture cost and CO_2 avoidance cost of the MEA-based carbon capture process vary from 59.8 to 63.1 €/tonne CO_2 and 82.7 to 87.0 €/tonne CO_2 with the increase in electricity price from 100 to 130 €/MWh. While, for the SPEI integration, the CO_2 capture cost and CO_2 avoidance cost vary from 48.2 to 51.4 €/tonne CO_2 and 60.2 to 64.2 €/tonne CO_2 respectively.

In this case, if a carbon tax is implemented on the CO_2 emissions from the cement plant (inc. direct and indirect emissions), the cost of clinker increased significantly for the reference cement plant. For a carbon tax at slightly above 60 €/tonne CO_2 the clinker cost with SPEI integration decreases compared to the reference cement plant. While, when the carbon tax at around 85 €/tonne CO_2 is implemented, the clinker cost from the MEA integration is lower compared to the reference plant.

3.2.3. Influence of heat recovery on key performance indicators

In the previous sections, the economic KPIs are only considered for the case with no heat recovery from the reference cement plant. Thus, the natural gas boiler provides all the heat required for sorbent regeneration. However, heat can be recovered from the reference cement plant and utilised for sorbent regeneration. A schematic diagram of heat recovery from the process is shown in Fig. 12. The flue gas leaving the preheater is at the temperature of 370 °C. The simulation results of energy balance show that a maximum of 53.9 MWth of heat can be recovered from the flue gas at the exit of 1st stage cyclone preheater. Therefore, to investigate the influence of heat recovery from the reference cement plant on external heat required and CO_2 emissions, the percentage of heat recovery is performed in the range of 0–100%. However, realistically around 60% of heat can be recovered from the flue gas.

It can be seen from Table 9 that as the heat recovery percentage increased from 0 to 100%, the total CO_2 emissions (inc. direct, indirect and from natural gas boiler) are reduced by 6.5% for the MEA integration and 6.9% for the SPEI integration scenarios due to the decrease in requirement of external heat. It can be depicted that the external heat requirement for MEA integration is decreased from 162.9 to 82.5 MWth. Additionally, the total CO_2 emissions from the process are decreased from 23.5 to 21.9 tonnes of CO_2/hr. Similarly, for SPEI integration, the external heat requirement is decreased from 102.4 to 30.8 MWth, and the total CO_2 emissions are decreased from 22.2 to 20.7 tonnes of CO_2/hr.

In addition, the economic KPIs are also accessed. As shown in Fig. 13, the CO_2 capture cost and CO_2 avoidance cost reduce with the increase in the percentage of heat recovered from the reference cement plant. With the increase in heat recovery percentage from 0 to 100%, the CO_2 capture cost of SPEI and MEA-based carbon capture process is reduced from 49.8 to 35.6 €/tonne CO_2 and 61.4 to 48.0 €/tonne CO_2 respectively. Likewise, the CO_2 avoidance cost of SPEI and MEA-based carbon capture process is reduced from 62.2 to 44.5 €/tonne CO_2 and 84.7 to 57.5 €/tonne CO_2 respectively. The reduction in the CO_2 capture cost and CO_2 avoidance cost is observed due to the utilisation of less natural gas which results in lower CO_2 emissions from natural gas and eventually low capital and operating costs. The CO_2 avoidance cost of integrating
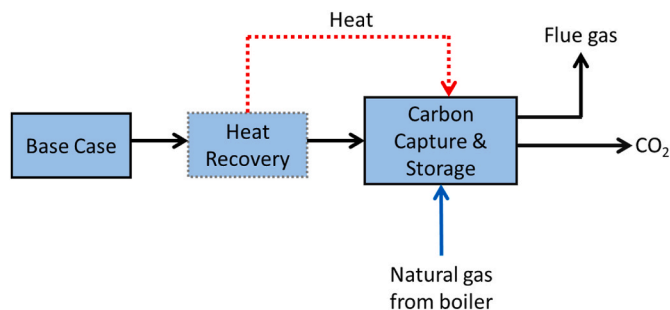
Table 9
Influence of heat recovery on heat requirements and CO_2 emissions.

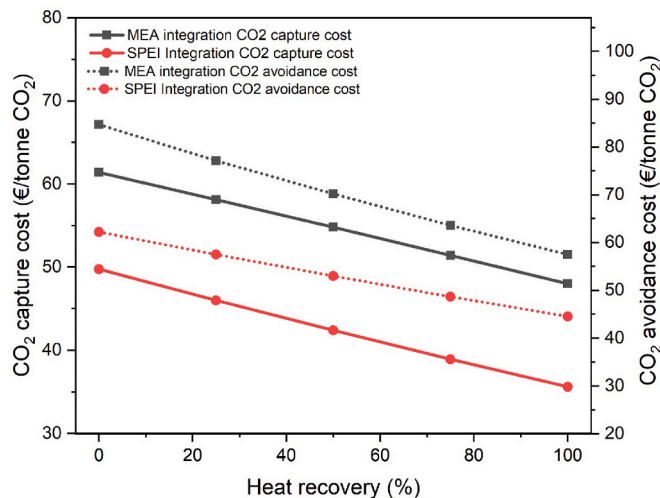|	Heat recovery				
	0%	25%	50%	75%	100%
Total heat required from natural gas boiler (MW$_{th}$)					
MEA integration	162.8	141.6	121.2	101.5	82.5
SPEI integration	102.4	83.4	65.1	47.6	30.8
Total CO_2 emissions (tonne/hr)					
MEA integration	23.5	23.1	22.7	22.3	21.9
SPEI integration	22.2	21.8	21.5	21.1	20.7
Total CO_2 reduction (%)					
MEA integration	0.0	1.6	3.2	4.9	6.5
SPEI integration	0.0	1.7	3.4	5.2	6.9

Fig. 13. Influence of heat recovery on CO_2 capture and CO_2 avoided costs.

various carbon capture technologies into cement plant was studied by Gardarsdottir et al. (2019). They found that, after integrating heat from the plant, the cost of CO_2 avoidance for MEA, chilled ammonia, membrane-assisted CO_2 liquefaction, calcium looping-tail end, and integrated calcium looping-based carbon capture processes were at 80.2, 66.2, 83.5, 52.4, and 58.6 €/tonne CO_2, respectively. These costs are higher than that of the SPEI-based carbon capture process, indicating the superiority of the novel SPEI-based process.

4. Conclusion

A detailed technoeconomic analysis of two post-combustion carbon capture processes (i.e., the MEA-based and SPEI-based carbon capture processes) has been undertaken. Based on our findings, the SPEI-based carbon capture process is more suitable for CO_2 capture in cement plants compared to the MEA-based carbon capture process. The following conclusions can be drawn from this study.

1. Both the studied processes can potentially remove $\geq$90% of the CO_2 from the flue gas. MEA-based carbon capture process shows the SPECCA at 6.5 GJ/tonne CO_2. While the SPECCA for the SPEI carbon capture process is lower compared to MEA based carbon capture process at 4.3 GJ/tonne CO_2.
2. The CO_2 capture cost of the MEA scrubbing process and SPEI-based processes is estimated at 61.4 and 49.8 €/tonne CO_2, respectively. The CO_2 avoidance cost of the MEA scrubbing and SPEI-based carbon capture process is estimated at 84.7 and 62.2 €/tonne CO_2, respectively.
3. The sensitivity analysis shows that the minimum carbon capture cost is observed at 55.4 and 45.7 €/tonne CO_2 for the MEA-based carbon

Fig. 12. Schematic diagram of heat recovery process.

capture process and SPEI-based carbon capture process when the natural gas price is 20 €/MWh.

4. If a carbon tax is implemented, the BESP of the reference cement plant increases significantly. At a carbon tax above 60 €/tonne CO_2, the cost of clinker produced with the cement plant integrated with the SPEI-based carbon capture process is lower than the reference cement plant. When the carbon tax is approximately 85 €/tonne CO_2, the BESP of the MEA-based carbon capture process is lower than the reference.

5. The reference cement plant can recover a maximum of 53.9 MWth of heat. If a 100% of the available heat is recovered from the reference cement plant, the total CO_2 emissions reduces to up to 6.5% for the MEA-based carbon capture process. While, for the emissions reduces to up to 6.9% for the SPEI-based carbon capture process.

6. In the case of the 100% heat recovery from the cement plant, the cost of CO_2 capture for the MEA-based and SPEI-based carbon capture processes reduces to 48.0 €/tonne CO_2 and 35.6 €/tonne CO_2, respectively. Furthermore, the CO_2 avoidance cost for the MEA-based and SPEI-based carbon capture processes reduces to 57.5 €/tonne CO_2 and 44.5 €/tonne CO_2, respectively.

CRediT authorship contribution statement

M.M. Jaffar: Investigation, Writing – original draft. **C. Brandoni:** Writing – review & editing. **J. Martinez:** Investigation, Writing – review & editing. **C. Snape:** Conceptualization, Investigation, Writing – review & editing. **S. Kaldis:** Investigation, Writing – review & editing. **A. Rolfe:** Writing – review & editing. **A. Santos:** Investigation, Writing – review & editing. **B. Lysiak:** Investigation, Writing – review & editing. **A. Lappas:** Investigation, Writing – review & editing. **N. Hewitt:** Supervision. **Y. Huang:** Conceptualization, Supervision, Writing – review & 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.

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