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Techno-economic assessment of hybrid CO₂ capture processes in cement manufacturing based on partial oxyfuel & post-combustion technologies

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Abstract

This work presents a techno-economic evaluation of a hybrid configuration combining partial oxyfuel with post-combustion CO₂ capture technologies. Process simulations show that the technology can achieve a remarkably high CO₂ capture potential of 99.1% and 87.0% of direct (i.e. scope 1) and equivalent (i.e. scope 1 and scope 2) CO₂ emissions, respectively, exceeding the values reported for benchmark cement plants with a post-combustion monoethanolamine (MEA) system (70.4% and 64.4%) or with oxyfuel technology (90.0% and 82.0%). In addition, the specific primary energy consumption for CO₂ avoided (*SPECCA*), which includes direct and indirect fuel consumption and emissions, is calculated to be 2.91 MJ_{LHV}/kg_{CO2} compared to 7.08 MJ_{LHV}/kg_{CO2} and 1.63 MJ_{LHV}/kg_{CO2} of the benchmark plants based on MEA and oxyfuel capture respectively. The combination of high capture rates and the utilization of waste heat result in a very competitive cost of avoided CO₂ of 55.4 €/t_{CO2} and a cost of clinker of 107.2 €/t_{cl}.

Keywords: carbon capture; cement production; partial oxyfuel; techno-economic analysis

1. Introduction

Cement production is estimated to be responsible for ~8% of global CO₂ emissions [1]. Because the majority of these emissions (~60%) arise from the calcination of CaCO₃ rather than the combustion of fuels, implementing Carbon Capture and Storage (CCS) methods is necessary to reach significant rates of CO₂ emissions reduction [2–4]. Several studies have identified CCS strategies to be deployed in the cement industry, including post-combustion capture using amines, chilled ammonia, membrane assisted CO₂ liquefaction, low temperature sorbents, Calcium Looping, or through oxyfuel and partial oxyfuel combustion [5–15].

Oxyfuel is considered among the most promising technologies for CO₂ capture in cement plants [8, 11]. The main concern in an oxyfuel cement plant is the dilution of the CO₂ stream by the ingress of false air, which ultimately affects the energy consumption and the CO₂ recovery rate of the CO₂ purification unit (CPU). According to AirLiquide and other partners in the AC²OCEM project, a variation of roughly ± 2% of specific energy demand for the design of the CPU can be expected for every ± 1% change in CO₂ concentration on a dry basis [16].

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Additionally, Magli et al. [17] found that in an economically optimized CPU, a reduction of the initial purity from 94.1% (no air infiltration) to 84.6% (10% air infiltration) involves a reduction of CO₂ recovery by 3.3 - 4.5% and increased clinker production costs by 3.3 - 4.0%, depending on the final target purity. This means that the sealings have to be significantly improved compared to a conventional plant, to ensure gas tightness operation. The possibility of ensuring tight sealing of the rotary kiln, the air cooler and the CO₂ recirculation equipment between maintenance periods is to be proven.

A promising alternative to overcome this barrier is to implement oxy-combustion only in the pre-calciner, while the operation of the rotary kiln and the air cooler remains unmodified. This partial oxyfuel configuration addresses the majority of the plant's emissions (~90 - 95% of process CO₂ emissions and ~60% of the emissions from fuel combustion), and puts the focus of the retrofitting efforts - for gas tightness and operation under oxy-combustion atmosphere - in the pre-calciner and the preheater tower only [5, 9, 11].

Another alternative is to capture the CO₂ using post-combustion methods, i.e. end-of-pipe technologies, which do not directly interfere with the cement manufacturing process, and are thus easier to implement in existing plants. Despite being a mature technology, the main drawback of post-combustion systems with amine solvents is the high energy consumption required for the regeneration step, estimated between 3 - 4 MJ/kg of captured CO₂ [18, 19]. With modern cement plants using a significant fraction of the available waste heat for raw material drying and raw meal heating, there is not much additional thermal energy to produce the necessary steam demand (above 120 - 125 °C). Previous studies have calculated the available waste heat for steam generation in the order of 0.15 - 0.25 MJ/kg of captured CO₂ [13, 20]. Therefore, only 3% - 8% of the energy penalty could be met using the plant available waste heat, and the supply of the remaining share increases considerably the cost of capturing the CO₂.

The scope of this work is to assess a hybrid configuration combining partial oxyfuel technology and post-combustion CO₂ capture to exploit the following synergies:

- Partial oxyfuel for low energy consumption and low cost CO₂ separation from the calcination process and the majority of the fuel-related emissions.
- Post-combustion capture of CO₂ from the flue gases of the rotary kiln using solvent-base process, effectively reducing the energy demand from the regeneration step.
- High CO₂ capture rate by recovering the CO₂ in the vent gas of the CPU in the post-combustion capture system.
- Use of the available waste heat from the III air to supply the energy demand to the post-combustion system.

2. Description of the process

Figure 1 shows a schematic of the assessed process. To avoid dilution of the CO₂-rich gas stream coming from the pre-calciner with the flue gases from the rotary kiln, two preheating strings (PHS) are needed (referred in this paper as calciner string and kiln string). The solid material from both strings is fed to the pre-calciner where ~93% of the calcium carbonate (CaCO₃) is decomposed into CaO and CO₂.

The endothermic calcination reaction occurring in the pre-calciner is responsible for the majority of the energy demand (~70%) which is provided by the combustion of coal in an oxygen-rich environment. Oxygen is supplied from an air separation unit (ASU) and the flow rate is adjusted to achieve an O₂ concentration at the outlet gas of the pre-calciner of 2.7 mol%, consistent with the operation of a conventional reference cement plant [13, 21]. Furthermore, fuels burned in an oxygen-rich environment have a high combustion temperature; therefore, part of the CO₂-rich gas exiting the calciner string needs to be recycled back to the calciner inlet to moderate the temperature. The rest of the CO₂ is sent to the CPU unit after pre-heating the oxygen stream from the ASU and generating steam for the post-combustion system.

Because the calcination occurs under higher CO₂ partial pressure, the pre-calciner's exit temperature is increased to 920 °C (~60 °C higher than conventional operation) to achieve a similar calcination degree.

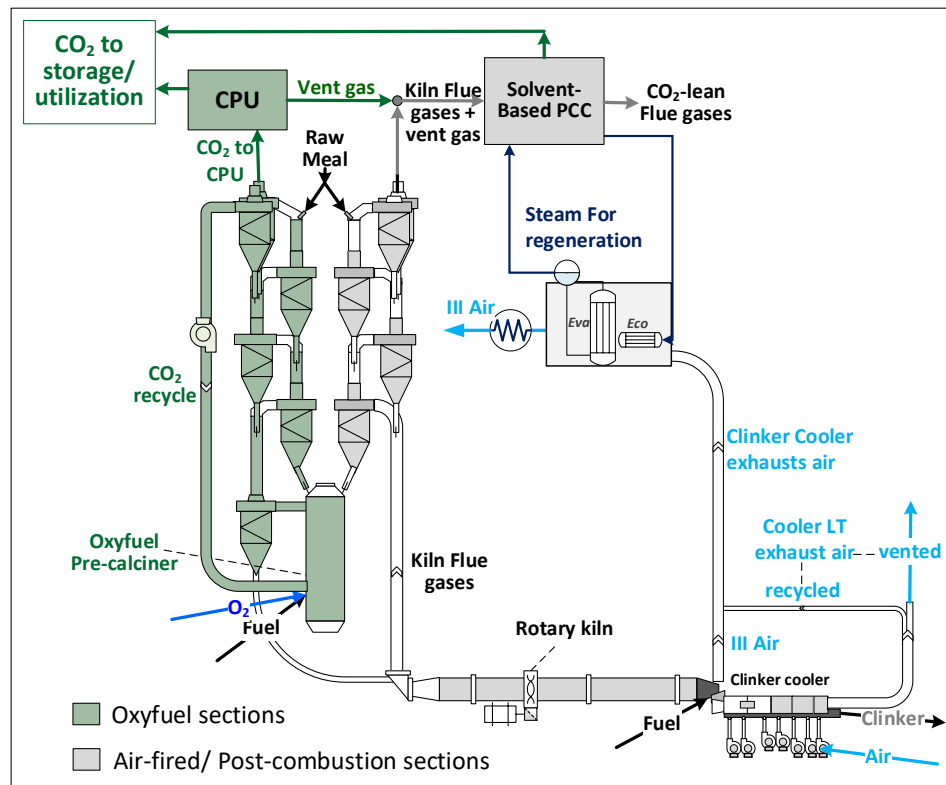


Figure 1: Schematic of the proposed hybrid partial oxyfuel – post-combustion capture configuration

In the rotary kiln, the calcination of the remaining CaCO_3 is completed and the formation of the clinker phases is achieved. The remaining necessary heat ($\sim 30\%$) is supplied by combusting coal in a burner at the hot end of the kiln, using secondary air from the clinker cooler along with primary and transport air for the fuel. At the exit of the kiln string, the flue gases are sent to the post-combustion capture system, where they are treated together with the vent gas arising from the CPU.

The clinker cooler is the final stage, designed to rapidly reduce the temperature of the hot clinker and preserve its composition. The heat from the exiting air is utilized within the process by diving it into secondary air, tertiary air, and vent air. Secondary air is used as combustion air for the kiln's burner. Tertiary air is conventionally used as combustion air for the pre-calciner. However, in the proposed hybrid partial oxyfuel-MEA model, the available heat from the tertiary air and the vent air is combined and used to produce steam for the post-combustion system and to dry the raw materials in the raw mill.

The post-combustion CO_2 capture system is based on absorption using MEA. The configuration of the process is depicted in Figure 2 and it is consistent with the work carried out in the CEMCAP project [13]. The absorber is divided in two sections, the bottom one operating with the MEA solvent and a top section operating as a water wash. Lean solvent enters the absorber column (#11) and captures the CO_2 from the flue gases of the kiln string (#5) and the vent gases from the CPU (#6) before exiting as rich solvent from the bottom (#8). Recirculation of the MEA solvent is adjusted to achieve a carbon capture rate (CCR) of 95.9%.

The rich solvent is then heated and sent to a stripper column where CO_2 is released from the solvent with a purity of 99.9% on dry basis (#12). Afterwards, CO_2 is dried and compressed to 110 bar to meet the requirements for pipeline transport (#13). The steam required for the regeneration step is completely supplied by the available waste heat from the flue gases of the kiln string (Q-01), the CO_2 from the calciner string (Q-02), and the combination of II air and III air coming from the clinker cooler (Q-03).

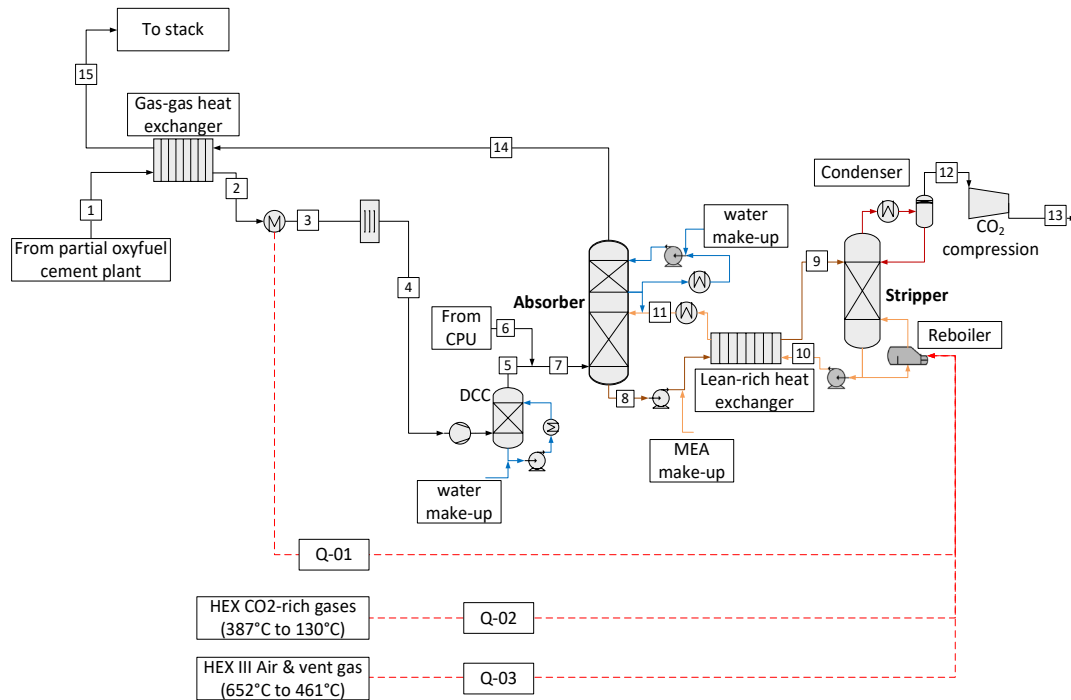


Figure 2: Schematic of the post-combustion MEA system

3. Methods

The heat and mass balances for the hybrid configuration were calculated using Aspen Plus v10.

Assumptions used for the simulations are consistent with the ones used in the framework of the CEMCAP project and other simulation studies [7, 15, 22]. These can be found in Table 1.

Table 1: Main assumptions for the simulation of the hybrid partial oxyfuel-MEA configuration

| Hybrid partial oxyfuel-MEA | Value | Unit |
|---|--------|----------------------|
| <i>Clinker manufacturing process</i> | | |
| Clinker production | 2,825 | tpd |
| Clinker/cement factor | 0.737 | |
| Calcination degree at pre-calciner's outlet | 92.3 | % |
| Ratio of false air to the inlet gas of each stage in the preheating tower | 1.6 | % |
| Number of stages in the kiln string | 3 | |
| Number of stages in the calciner string | 3 | |
| O ₂ concentration in the CO ₂ /O ₂ mixture | 50 | % |
| Electricity consumption of auxiliaries | 97 | kWh/t _{cem} |
| Secondary and tertiary air temperature | 1,137 | °C |
| Tertiary air volumetric flowrate (same as reference plant) | 73,246 | Nm ³ /h |
| <i>Air Separation Unit</i> | | |
| O ₂ purity | 95 | %vol. |
| Electricity consumption | 230 | kWh/to ₂ |
| <i>CO₂ Compression and Purification Unit</i> | | |
| Pressure in the liquid-vapor separator | 38 | bar |
| Temperature in the liquid-vapor separator | -48 | °C |
| Number of LP/HP intercooled compression stages | 4 / 2 | |
| CO ₂ target purity | 99.99 | %vol. |
| CO ₂ final pressure | 110 | bar |
| <i>MEA post-combustion capture system</i> | | |

| | | |
|---|------|----------------------|
| CO ₂ capture efficiency | 95.9 | % |
| Lean solvent charge | 0.24 | |
| Absorber diameter | 4.2 | m |
| Absorber height (without water wash) | 20 | m |
| Absorber height (only water wash) | 3 | m |
| Number of stages in the absorber (without water wash) | 50 | |
| Number of stages in the absorber (only water wash) | 10 | |
| Reboiler operating pressure | 2 | bar |
| Reboiler operating temperature | 122 | °C |
| Heat demand in the reboiler | 3.77 | MJ/kg _{CO2} |

Key Performance Indicators (KPI) consistent with the CEMCAP framework [13] have been used to assess the CO₂ emissions, the energy consumption and the economic performance of the hybrid partial oxyfuel-MEA configuration. In addition to direct emissions and consumptions (i.e. Scope 1), indirect (i.e. Scope 2) and equivalent (i.e. Scope 1 + Scope 2) emissions are computed considering an average electric efficiency of 45.9% and specific emissions of 262 kg_{CO2}/MWh for the grid. The KPIs are compared with a reference cement plant without CO₂ capture, one with a post-combustion capture system using MEA absorption, and one operating with full oxyfuel technology. The results for the conventional cement plant, the plant using the MEA absorption, and the one using oxyfuel are gathered from the outcomes of the CEMCAP project [13].

4. Results

Table 2 shows the results of the mass and energy balance for a hybrid partial oxyfuel-MEA cement plant designed with 3 stages in each preheating string and a CO₂ recycle rate to reach an O₂ concentration of 50% in the burner of the pre-calciner.

Table 2: Mass and energy balance of the simulated cement plant with hybrid partial oxyfuel-amine capture process

| Item | Value |
|---|--------|
| Raw meal inlet (kg/s) | 54.72 |
| <i>Kiln string</i> | |
| Raw meal split (%) | 45.7 |
| Temperature of flue gases (°C) | 269 |
| Temperature in bottom stage (°C) | 750 |
| Solid-to-gas ratio (kg/kg) ^a | 1.41 |
| <i>Calciner string</i> | |
| Raw meal (%) | 54.3 |
| Temperature of flue gases (°C) | 415 |
| Temp in bottom stage (°C) | 795 |
| Solid-to-gas ratio (kg/kg) ^a | 0.79 |
| CO ₂ recycle (Nm ³ /h) | 19,324 |
| <i>Fuel consumption</i> | |
| Fuel demand in pre-calciner (MJ/kg _{clik}) | 2.83 |
| Fuel demand in rotary kiln (MJ/kg _{clik}) | 1.18 |
| Fuel consumption increase with respect to the reference (%) ^b | 25 |
| Available heat recoverable for amine regeneration (MW _{th}) ^c | 34.9 |
| Available heat recoverable for amine regeneration (MJ/kg _{CO2}) ^c | 5.7 |
| <i>CO₂ balance</i> | |
| CO ₂ from the rotary kiln (kg _{CO2} /t _{clik}) | 149.8 |
| CO ₂ at CPU inlet (kg _{CO2} /t _{clik}) | 786.9 |
| Purified CO ₂ from the CPU (kg _{CO2} /t _{clik}) | 739.3 |
| CO ₂ released in the vent from the CPU (kg _{CO2} /t _{clik}) | 47.6 |
| CO ₂ to the MEA system (kg _{CO2} /t _{clik}) | 197.4 |

| | |
|--|-------|
| Compressed CO ₂ to storage (kgCO ₂ /t _{clk}) | 928.6 |
|--|-------|

^a Solid-gas ratios are calculated as the raw meal feed / gas entering the bottom stage of the string.

^b Compared to the reference cement plant without CO₂ capture with a total fuel consumption of 3.24 MJ/kg_{clk} [13].

^c Includes the heat available from the flue gases of the kiln string, from the CO₂ in the calciner string, and from the mixture of II and III air at temperature higher than 130 °C.

It is interesting to notice that the waste heat available is enough to satisfy the energy demand from the regeneration step of the amine-based absorption system (calculated at 3.77 MJ/kgCO₂), which is designed to treat both the CO₂ exiting with the flue gases of the kiln string and the CO₂ in the vent of the CPU. From the mass and energy balances, the total waste heat available in the plant adds to 34.9 MW_{th} or 5.7 MJ/kgCO₂. This was estimated for the production of steam at 120 °C, considering a temperature difference of 10 °C in the outlet of the hot gas stream (i.e., 130 °C). Supplying the necessary energy for the regeneration step using the waste heat from the process has a huge impact on the economic performance of the post-combustion system.

The KPIs of the hybrid partial oxyfuel-MEA technology are reported in Table 3. The values are contrasted with the emissions reduction potential of a benchmark cement plant with a post-combustion CO₂ capture system based on MEA and a full oxyfuel plant.

Table 3: KPIs for the CO₂ emissions abatement potential

| KPI | Reference plant | Hybrid partial oxyfuel-MEA | Post-combustion MEA | Oxyfuel |
|---|-----------------|----------------------------|---------------------|-------------------|
| Direct fuel consumption (MJ _{LHV} /kg _{clk}) | 3.24 | 4.01 | 6.31 ^a | 3.25 |
| Indirect fuel consumption (MJ _{LHV} /kg _{clk}) | 0.47 | 1.50 | 0.89 | 1.17 ^b |
| Power demand from ASU (MW _{el}) | - | 6.6 | - | 7.1 |
| Power demand from CPU (MW _{el}) | - | 12.7 | - | 11.4 |
| Power demand from CO ₂ compression (MW _{el}) | - | 2.1 | 8.6 | - |
| Power demand from other auxiliaries ^c (MW _{el}) | - | 1.1 | 4.7 | 1.8 |
| Equivalent fuel consumption (MJ _{LHV} /kg _{clk}) | 3.71 | 5.51 | 7.20 | 4.41 |
| Direct CO ₂ emissions (kgCO ₂ /t _{clk}) | 865.2 | 8.1 | 256.0 ^d | 88.0 |
| Indirect CO ₂ emissions (kgCO ₂ /t _{clk}) | 34.5 | 109.4 | 64.6 | 85.1 |
| Equivalent CO ₂ emissions (kgCO ₂ /t _{clk}) | 899.7 | 117.5 | 320.6 | 173.1 |
| Direct CO ₂ emissions avoided (%) | - | 99.1 | 70.4 | 90.0 |
| Equivalent CO ₂ emissions avoided (kgCO ₂ /t _{clk}) | - | 87.0 | 64.4 | 82.0 |
| CO ₂ purity (%mol) | - | 99.9 | 99.8 | 97.3 |
| SPECCA (MJ _{LHV} /kgCO ₂) | - | 2.91 | 7.08 ^e | 1.63 ^e |

^a Includes the consumption of a natural gas boiler to produce steam for the regeneration step.

^b Includes the power generation from an organic Rankine cycle

^c Includes also the power consumption of thermal reclaimer (MEA), pumps, fans, cooling water system, etc.

^d Includes the emissions from the natural gas combustion in the boiler.

^e The SPECCA was estimated using 844 kgCO₂/t_{clk} of direct CO₂ emissions in the reference plant.

Both direct and indirect fuel consumption increase in the hybrid partial oxyfuel-MEA design with respect to the reference plant without capture. The variation in direct fuel demand is mainly attributed to the fact that in the pre-calciner a mixture of CO₂/O₂ is used as oxidant at lower temperature (308 °C) compared to tertiary air at ~1000 °C. In this case, the available heat from the hot tertiary air stream is exploited to produce steam for the post-combustion system. This allows avoiding additional fuel consumption for amine regeneration, which can be evidenced when comparing the direct fuel demand of the hybrid design (4.01 MJ_{LHV}/kg_{clk}) with that of the MEA system (6.31 MJ_{LHV}/kg_{clk}). The latter includes the consumption of a natural gas boiler to produce steam. The lack of available heat to supply the steam requirement for the regeneration step is the main drawback for implementing solvent-based CO₂ capture technology alone. On the other hand, the need of O₂ for the oxyfuel combustion in the pre-calciner and the treatment of the CO₂-rich gas requires more electric power compared to the benchmark MEA case. The results show that approximately 56% of the increase on indirect fuel consumption comes from the CPU, while the rest is associated to the ASU (29%), CO₂ compression from the MEA system (9%), and other auxiliaries (5%).

The overall treatment of the flue gases from the process, including the vent air of the CPU allows for a high capture rate of 99.1% of direct CO₂ emissions, while achieving very high CO₂ purity of 99.9%. When indirect

emissions from the electricity network are added, the CO₂ emission abatement reduces to 87.0%, as a consequence of the specific emission intensity of the grid. Nonetheless, these values are extremely promising, especially when compared against the evaluation of the reference CO₂ capture system with MEA absorption. Even when compared against the assessment of other technologies with high decarbonization potential [13], such as oxyfuel ($AC_{eq} = 82\%$), the hybrid partial oxyfuel-MEA configuration stands out as the system with the highest CO₂ emission reduction potential. It is worth noting that the assessment of the MEA system and the CPU in [13] assumes a capture rate of 90%, while in this work a capture rate of 95.6% and 94.0%, respectively, were considered.

Finally, the *SPECCA* of the hybrid partial oxyfuel-MEA configuration is 2.4 times lower than the one from the reference MEA system. From the work conducted in the framework of the CEMCAP project, the only technology with a lower *SPECCA* is oxyfuel, with a calculated value of 1.63 MJ/kgCO₂ [13]. The largest contributions to the *SPECCA*, detailed in Figure 4, come from CO₂ purification and compression and from the additional fuel demand in the clinker manufacturing process, followed by the power demand in the ASU, the CO₂ compression from the MEA stripper, and other auxiliaries such as pumps, fans, etc. The fact that the indirect fuel consumption accounts for 66% of the *SPECCA* highlights the relevance of the characteristics of the electricity network in terms of generation efficiency (η_e) and specific CO₂ emissions (e_{el}).

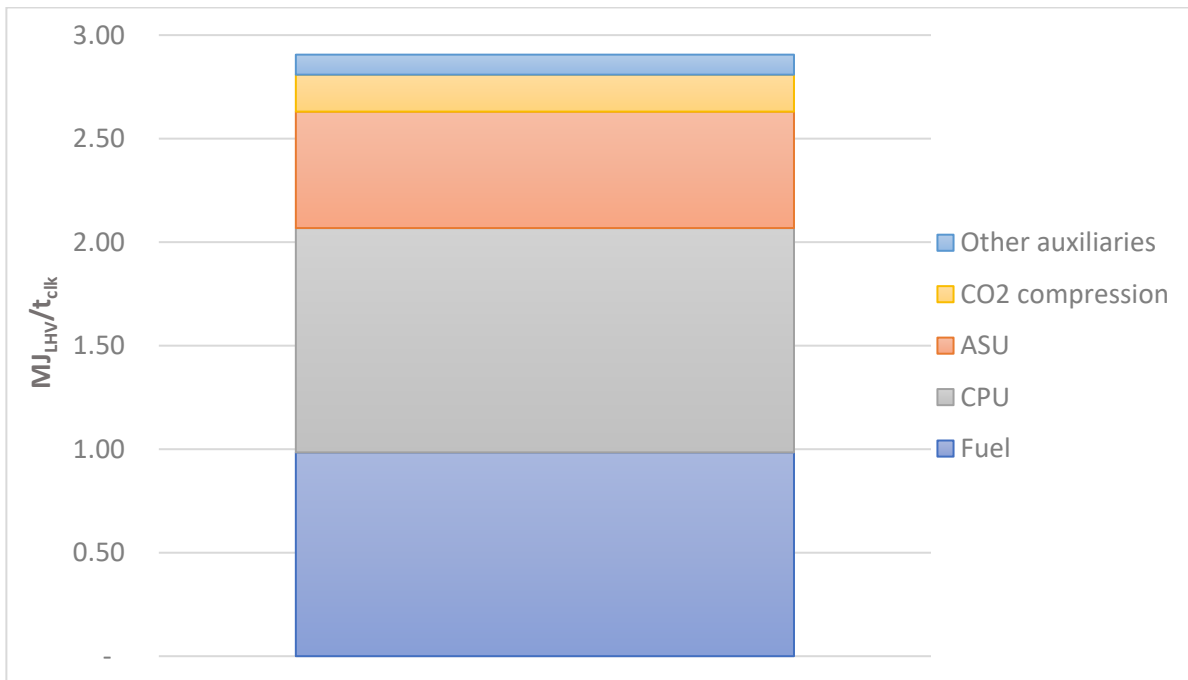


Figure 3: Breakdown of *SPECCA* for the hybrid partial oxyfuel-MEA technology

The economic analysis of the technology was conducted by estimating the CAPEX, OPEX, the costs of clinker and the cost of avoided CO₂. All the values are reported in €₂₀₁₄, consistent with the methodology used in the CEMCAP project. The results, summarized in Table 4, show that the hybrid configuration entails a similar increase in the cost of producing 1 kg of clinker with respect to the reference post-combustion capture with MEA absorption. However, the high level of CO₂ capture reduces the cost of CO₂ avoided to 55.4 €/t_{CO2} under the assessed conditions. This value represents 69% of the cost of avoiding 1 ton of CO₂ using a post-combustion system with MEA, and it is 23% higher than the one reported for the oxyfuel process (42.4 €/t_{CO2}).

Table 4: Economic KPIs for the partial oxyfuel-MEA configuration

| Item | Reference | Hybrid partial oxyfuel-MEA | Post-combustion MEA | Oxyfuel |
|------|-----------|----------------------------|---------------------|---------|
|------|-----------|----------------------------|---------------------|---------|

| | | | | |
|---|-------|-------|-------|-------|
| Capex (M€) | 204 | 334 | 280 | 332 |
| Opex (€/t _{clik}) | 42 | 72 | 78 | 59 |
| Cost of clinker (€/t _{clik}) | 62.6 | 107.2 | 107.4 | 93.0 |
| Cost of CO ₂ avoided (€/t _{CO2}) | - | 55.4 | 80.2 | 42.4 |
| <i>Cost of CO₂ avoided with different carbon tax (€/t_{CO2})</i> | | | | |
| COC with carbon tax of 50 €/t _{CO2} | 108.8 | 113.1 | 123.8 | 101.7 |
| COC with carbon tax of 100 €/t _{CO2} | 153.8 | 118.9 | 140.2 | 110.3 |
| COC with carbon tax of 150 €/t _{CO2} | 198.8 | 124.8 | 156.5 | 119.0 |

Furthermore, the sensitivity of the *COC* was evaluated against the price of the carbon tax. By capturing the majority of the CO₂ emissions, the hybrid partial oxyfuel-MEA process becomes economically competitive against a reference plant without CCS at a carbon tax of ~56 €/t_{CO2}. With respect to the cement plants using other CO₂ capture technologies, the results indicate that the *COC* of the hybrid configuration always stays below the cost of using a post-combustion MEA absorption system, while the crossover point with the oxyfuel process happens around a carbon tax of ~250 €/t_{CO2}.

The breakdown of the additional capital cost with respect to the reference cement plant is summarized in Table 5. Post-combustion capture with MEA results in the least investment with a total additional CAPEX of 76 M€, followed by the oxyfuel technology (128 M€), and the hybrid partial oxyfuel-MEA configuration (130 M€). To estimate the CAPEX of the hybrid case, the equipment was scaled based on the values reported in the CEMCAP project, adjusted by the different flowrates and a scaling factor of 0.6 for the ASU and 0.67 for the rest [7, 13].

Results show that 46.6% of the capital cost for the hybrid partial oxyfuel-MEA configuration comes from the CPU, followed by the ASU (31.6%) and the MEA system (19.3%) designed to treat the flue gases of the kiln string and the vent gases from the CPU.

The hybrid configuration is impacted by the use of two different technologies, which increase the total capital cost with respect to a post-combustion amine-based capture system. Nonetheless, this design offers some interesting flexibility in terms of implementing the technology that can benefit the investment schedule of a project. For instance, the post-combustion system can be commissioned at an earlier stage to treat a portion of the flue gases and adjust the operating conditions while the plant is preparing for a next round of modifications. The oxyfuel pre-calciner could then be implemented at a later time. Vice versa, the updates to the cement plant could start with the partial oxyfuel process and implement the post-combustion capture afterwards.

Another benefit is the use of the available waste heat from the process which eliminates the need to invest in a natural gas boiler.

Table 5: Additional CAPEX from CO₂ capture technologies

| Item | Hybrid partial oxyfuel-MEA | Post-combustion MEA | Oxyfuel |
|--------------------------------------|----------------------------|---------------------|------------|
| MEA capture unit (M€) | 9 | 24 | - |
| Direct contact cooler (M€) | 2 | 4 | - |
| Natural gas boiler (M€) | - | 13 | - |
| ASU (M€) | 41 | - | 43 |
| CPU/CO ₂ compression (M€) | 61 | 25 | 66 |
| Others (M€) | 18 | 11 | 20 |
| Total additional CAPEX (M€) | 130 | 76 | 128 |

The contributions to the *COC* and the *CAC* are detailed in Tables 6 and 7. The results show that there is a high influence of the CAPEX and the electricity demand on the economic performance of the hybrid partial oxyfuel-MEA plant.

Table 7 highlights the relevance of the electric power consumption in the cost of avoided CO₂. Indeed, the larger electricity demand from the ASU and the CPU affects both the technical and the economic performance. This is an aspect that represents a high level of uncertainty, given the fact that the outcome is dependent on the assumption for the electricity price.

Table 6: Breakdown of Cost of Clinker for the hybrid partial oxyfuel-MEA configuration

| Item | Hybrid partial oxyfuel-MEA | Post-combustion MEA | Oxyfuel |
|--|----------------------------|---------------------|-------------|
| Raw meal (€/t _{clk}) | 5.0 | 5.0 | 5.0 |
| Fuel (€/t _{clk}) | 12.0 | 9.4 | 9.4 |
| Electricity (€/t _{clk}) | 24.3 | 14.2 | 16.3 |
| Cooling water (€/t _{clk}) | 0.3 | 0.7 | 0.3 |
| Natural gas (€/t _{clk}) | - | 18.4 | - |
| Other variable costs (€/t _{clk}) | 3.4 | 6.1 | 1.7 |
| Variable OPEX (€/t _{clk}) | 45.0 | 53.8 | 32.8 |
| Labour | 11.0 | 10.6 | 10.7 |
| Insurance and local tax | 7.1 | 6.1 | 6.9 |
| Maintenance cost | 8.9 | 7.5 | 8.6 |
| Fixed OPEX (€/t _{clk}) | 27.0 | 24.2 | 26.2 |
| CAPEX (€/t _{clk}) | 35.2 | 29.4 | 33.6 |
| Cost of Clinker (€/t_{clk}) | 107.2 | 107.4 | 93.0 |

Table 7: Breakdown of the cost of avoided CO₂ for the hybrid partial oxyfuel configuration

| Item | Hybrid partial oxyfuel-MEA | Post-combustion MEA | Oxyfuel |
|---|----------------------------|---------------------|-------------|
| Fuel (€/t _{CO2}) | 2.95 | - | 0.02 |
| Electricity (€/t _{CO2}) | 21.23 | 11.73 | 12.10 |
| Natural gas for steam production (€/t _{CO2}) | - | 32.98 | - |
| Other variable costs (€/t _{CO2}) | 2.57 | 9.05 | 0.93 |
| Variable OPEX (€/t _{CO2}) | 26.76 | 53.76 | 13.04 |
| Fixed OPEX (€/t _{CO2}) | 10.60 | 10.66 | 11.20 |
| CAPEX (€/t _{CO2}) | 18.04 | 15.78 | 18.15 |
| Cost of avoided CO₂ (€/t_{CO2}) | 55.40 | 80.20 | 42.4 |

5. Conclusions

This work assessed the techno-economic performance of a hybrid configuration combining partial oxyfuel technology and post-combustion CO₂ capture with MEA. The results from analyzing the mass and energy balances carried out in Aspen Plus allow to reach the following conclusions:

- The hybrid partial oxyfuel configuration can achieve very high capture efficiencies by treating the flue gases of the rotary kiln and the vent stream of the CPU. Results indicate an abatement potential of 99.1% of scope 1 emissions and 87% of scope 2 emissions under the assumed conditions for the grid. These values exceed the ones reported in the CEMCAP project for benchmark post-combustion MEA system and full oxyfuel process.
- By reducing the amount of flue gases to be treated in the post-combustion system, the steam demand of the amine-regeneration step can be supplied entirely using the available waste heat from the clinker production process.
- The *SPECCA* of the assessed hybrid technology (2.91 MJ_{LHV}/kgCO₂) is 2.4 times lower than the one calculated for the reference CCS process with MEA (7.08 MJ_{LHV}/kgCO₂), but still higher than the one estimated for oxyfuel (1.63 MJ_{LHV}/kgCO₂).
- The results from the economic evaluation show a competitive cost of clinker (107.2 €/t_{clk}) and cost of CO₂ avoided (55.4 €/t_{CO2}). Higher CAPEX and the additional fuel consumption in the pre-calciner result in higher *COC* and *CAC* than the one reported for the oxyfuel process. However, the performance of the oxyfuel process is assessed for a final CO₂ purity of 97.4%, while the hybrid configuration achieves a higher purity of 99.9%.

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