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Techno-economic analysis of MEA CO_2 capture from a cement kiln – impact of steam supply scenario

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Abstract

This paper present the techno-economic assessment of an MEA-based CO_2 capture from a cement plant and the importance of the steam supply on the costs. The evaluations present the energy performances of the CO_2 capture process based on a cement plant with a clinker capacity of 3,000 t/d. The cost evaluation lead to a cost of cement of 45 €/t_{cement} without capture, while the cost of cement with CO_2 capture is estimated to 81 €/t_{cement}, resulting in a CO_2 avoided cost of 83 €/$t_{CO2,avoided}$.

As the steam consumption accounts for close to half of the CO_2 avoided cost, the impact of six alternative steam supply scenarios are considered. The evaluations show that the CO_2 avoided cost can decrease by up to 35% depending on the steam supply and electricity price. However the possibility of these steam supply alternatives are specific to the considered cement plant, emphasizing therefore that CO_2 avoided cost from cement shall rather be given as a range depending on the steam supply than as a unique value as often illustrated in the literature.

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Keywords: CCS; Cement; MEA-based capture; Techno-economic analysis; steam.

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1. Introduction

CEMCAP is a European R&D project under the Horizon 2020 Programme preparing for the large-scale implementation of CO_2 capture in the European cement industry [1]. This project aims to provide techno-economic background to support deployment of CO_2 capture in the European cement industry. In order to do so, CEMCAP investigate the technical and cost performances of five possible CO_2 capture technologies: 1) MEA-based capture (reference concept) 2) chilled ammonia capture 3) membrane assisted liquefaction 4) calcium looping 5) oxy-fuel. Assessment of pilot-scale test results and the iteration of experimental and analytical research for these technologies will provide a strategic techno-economic decision basis for CO_2 capture in the European cement industry.

Over the last decades, research and development of CO_2 capture has been most focused on CO_2 capture from power plants [2-4]. At such plants, steam for solvent regeneration can be extracted at the plant. However, this is not necessarily the case for CO_2 capture from other industries. In the case of CO_2 capture from a cement kiln there is no steam available at the plant and only very limited amount of waste heat. However, there may be several possible options for steam supply. This work therefore investigates the impact of the steam supply scenario on the cost of MEA-based CO_2 capture from a cement kiln.

2. Cement plant overview

The cement plant considered in this study is the reference cement plant of the CEMCAP project. This plant is a Best Available Technique (BAT) plant. It is based on a dry kiln process, and consists of a five-stage cyclone preheater, calciner with tertiary duct, rotary kiln and grate cooler. It has a clinker capacity of 3,000 t/d, which is a representative size for European cement plants. A flowsheet of the burning line of the reference cement plant is shown in Figure 1. Characteristics of the plant are listed in Table 1.

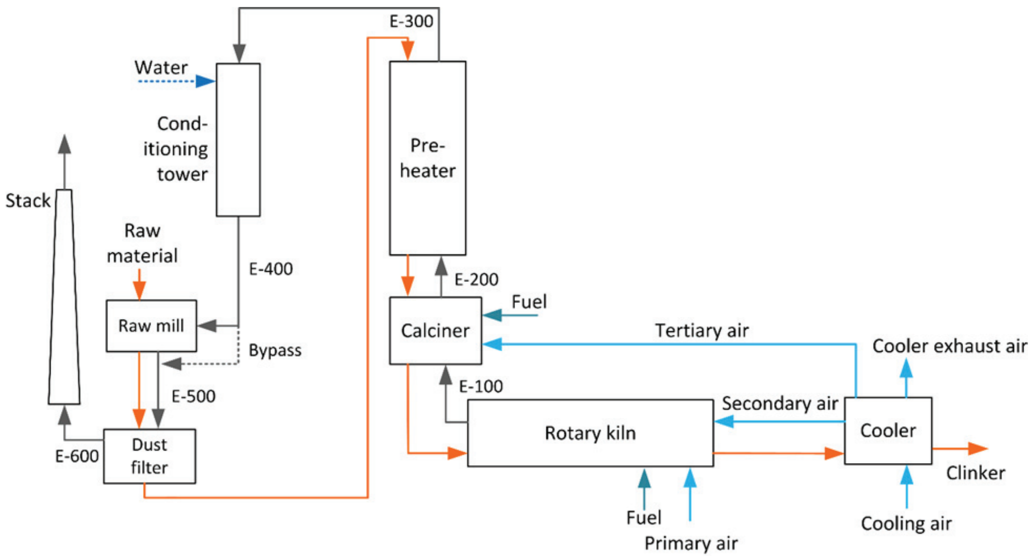

Figure 1: Flowsheet of the reference cement burning line. Dashed streams are relevant for direct operation. The lower cyclone in the preheating tower (the calciner cyclone) is considered as a part of the calciner.

Table 1. Characteristics of the cement plant.

Parameter	Value
Production capacity, Mtclk/y (tclk/d)	1 (3,000)
Cement production, Mtcement/y	1.36
Clinker/cement factor	0.737
Raw meal/clinker factor	1.6
Clinker, kg/s	33.51
Total fuel input (coal), kg/s	3.87
Total fuel input (coal), MW_{LHV}	104.47
Total electricity demand, MW_{el}	15.9
Direct CO_2 emissions, kg_{CO2}/tcement	622
Direct and indirect CO_2 emissions, kg_{CO2}/tcement	652

The raw material entering the burning line is first grinded and dried in the raw mill. The drying is done by hot flue gas that is sent to the mill from the preheater. Gas and the produced raw meal are subsequently separated in a dust filter, and the raw meal is sent to the preheater while the gas is sent to the stack.

In the preheater the meal is heated by hot gas coming from the calciner and the rotary kiln. The meal and the hot gases are mixed (for heat transfer) and separated in cyclones arranged above one another. The preheated raw meal is sent to the calciner, where the major part of the calcination of the raw meal ($CaCO_3$ -> CaO + CO_2) is performed. Around 2/3 of the plant's total fuel input is consumed here in order to achieve the right temperature (~860 °C) and drive the endothermal reaction.

The completion of calcination and the formation of the clinker phases take place in the rotary kiln. Around 1/3 of the plant's fuel is burnt in the rotary kiln burner. In the rotary kiln the solid material reaches 1450 °C, and the temperature of the gas phase can reach 2,000 °C. During its way through the rotary kiln the raw material components form clinker via intermediate phases.

The hot clinker is discharged from the kiln to a grate cooler. Here, cooling air flows through it from below. The cooler generates secondary air, which is preheated combustion air sent to the main burner in the rotary kiln, and tertiary air, which is preheated combustion air sent to the calciner.

Flue gas is produced by the burning of fuel in the rotary kiln and calciner, and by calcination of the raw meal in the calciner. The flue gas conditions are highly dependent on air leak throughout the burning line. The amount of air leak increases slowly under operation, but is reduced during maintenance (typically 1 or 2 times during the year). In this work the air leak is taken as defined in a BAT plant [5] the first ½ of the year, and the air leak in the raw mill (the major part of the total air leak) is doubled in the second ½ of the year.

Furthermore, a cement kiln switches between so-called interconnected and direct mode of operation during the day (depending on whether the raw mill is in operation or not). This has an impact on the resulting flue gas characteristics, and capture of CO_2 in direct operation is cheaper than in interconnected operation. However, the effect of this is neglected in this work, because a cement plant is typically only operated in direct operation in maximum 10% of the day.

The flue gas conditions considered in this work is given in Table 2. The contents of SO_x and NO_x are given in Table 3.

Table 2. Flue gas conditions at stack.

	First ½ year	Second ½ year
Total flow rate, kg/h	318,192	388,098
Temperature, °C	130	110
Gas phase composition, wet basis, vol%		
CO_2	22	18
N_2	60	63
O_2	7	10
H_2O	11	9

Table 3. Impurity concentrations at 10% O_2 content.

Component	Value
NO and NO_2, expressed as NO_2, g/m^3_{STP}	0.5
SO_2 and SO_3, expressed as SO_2, mg/m^3_{STP}	200

Heat can be recovered from the cooler exhaust gas. For the case of MEA CO_2 capture, saturated steam at around 125 °C is required, and 6.4 MW of heat can be recovered from the cooler exhaust gas to produce part of this steam.

3. Simulation of MEA CO_2 capture

The MEA capture process applied in this study is shown in Figure 2. The CO_2 rich flue gas is cooled against the CO_2 lean flue gas before being further cooled in a direct contact cooler (DCC). A major portion of water vapor in the CO_2 rich flue gas is removed in the DCC. The flue gas is then slightly compressed in a fan before being sent to the absorber where the CO_2 is absorbed by the MEA solvent. The CO_2 lean flue gas from the top of the absorber enters a water wash column where MEA is recovered. The flue gas is then heated to around 72 °C against the CO_2 rich flue gas before being vented into the atmosphere. The heating is necessary to ensure the spread and distribution of flue gas from the stack [6].

The rich MEA solvent from the bottom of the absorber is pumped and heated against the lean MEA solvent for heat recovery before being sent to the regenerator. The released CO_2 is recovered from the top of the regenerator and compressed to the target pressure by three compression stages with intercooling and a pump with an aftercooler. The major portion of water vapor in the CO_2 is condensed in the knockout (KO) drum. Another KO drum and a TEG dryer is used to further remove the water to meet the water specification in the captured CO_2. The lean MEA solvent from the reboiler is sent to the absorber after being pumped, cooled and mixed with the following 3 streams: (1) makeup water, (2) makeup MEA, and (3) the mixture of water and MEA recovered from the bottom of the water wash column. A pump and a water cooler are used to pressurize and cool the water from the bottoms of both the DCC and the water wash column. Notice that the water condensed in the DCC and the condenser of the regenerator is sent back to the water wash column for water recovery.

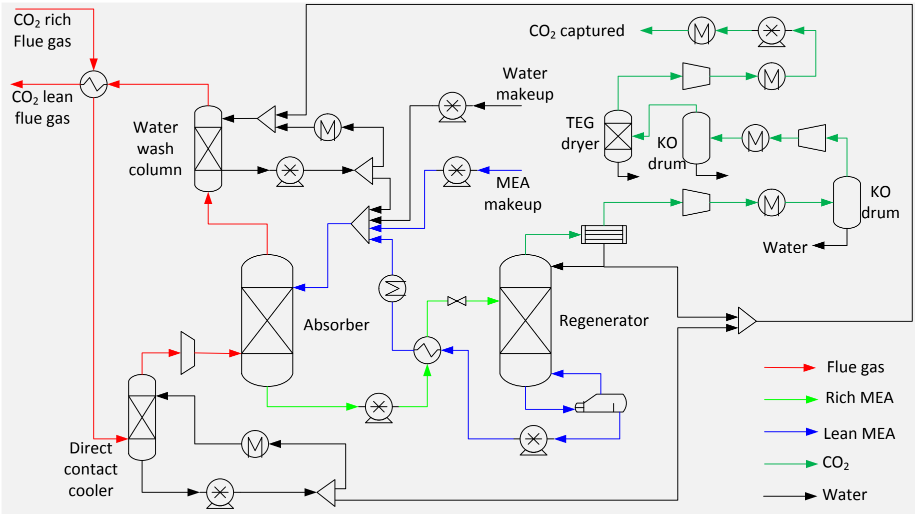

Figure 2. The MEA CO_2 capture process.

The entire process is modelled with the process simulator Aspen HYSYS V8.8. The Acid Gas property package is selected for modelling processes including MEA solvent. The SRK property package is used for calculating properties of the flue gas and CO_2 streams. Detailed sizing studies for the four packed columns (Absorber, Regenerator, Direct contact cooler and Water wash column) are performed in the column design software SULCOL (version 3.2.20). The column designs in the SULCOL program are based on actual operating results of many industrial applications as well as some laboratory measurements. The stream data information for the four columns are extracted from Aspen HYSYS to SULCOL. In this study, the main outputs from SULCOL include the diameters and heights of the packed columns as well as the column pressure drops. The main results from the process modelling such as the consumptions in work, heat and cooling duties as well as the solvent makeup are validated with other two public reports [2, 7]. The results are close and the differences can be well explained by the different process configurations and operating parameters.

The main results of MEA CO_2 capture are presented in Table 4. The compression work is the same for the three cases and the auxiliary work is slightly different due to different amount of gas and CO_2 being processed. Mainly due to different CO_2 fractions in the flue gas to be processed in the capture unit, the heat consumptions are different: the higher the CO_2 fraction is, the less is the heat consumption. The cooling duty is quite different for several reasons, e.g. (1) the flue gas temperatures are different, and (2) the heat consumptions are different.

Table 4. Main results of MEA CO_2 capture

Cases	First ½ year	Second ½ year
CO_2 mole fraction in captured CO_2 (wet basis)	0.9983	0.9983
Pressure of captured CO_2, bar	110	110
CO_2 capture rate	0.8994	0.8996
CO_2 compression work, MJ/kg_{CO2}	0.3142	0.3143
Auxiliary power for capture, MJ/kg_{CO2}	0.1274	0.1418
Total work consumption, MJ/kg_{CO2}	0.4416	0.4561
MEA mass fraction in lean MEA,	0.2998	0.3005
CO_2 lean loading, mol_{CO2}/mol_{MEA}	0.2705	0.2702
CO_2 rich loading, mol_{CO2}/mol_{MEA}	0.4953	0.4904
Heat consumption, MJ/kg_{CO2}	3.790	3.832
Reboiler temperature, ºC	116.8	116.8
Steam pressure, bara	2.45	2.45
Cooling duty, MJ/kg_{CO2}	4.598	4.909
Solvent (30wt% MEA) makeup, $kg_{Solvent}/t_{CO2}$	4.677	4.677

4. Economic analysis of the reference cement plant with MEA CO_2 capture

4.1. Cost evaluation methodology and results for the base case

A bottom up approach is here used to estimate the investment cost of the cement plant with and without CO_2 capture. In this approach, the assessed total direct cost of the plant are multiplied with EPC and TPC cost factors (see Table 5) to obtain the total plant cost. While the direct cost of the cement plant, the SCR and FGD are scaled from IEAGHG [7, 8] and updated using the CEPCI, the direct cost of the CO_2 capture and conditioning units are assessed based on the process design and commercial software.

The fixed operating cost which include maintenance, insurance and labour costs are assessed based on the methodology presented in Table 5 while the operating cost are based on the estimated utilities consumption and the utilities costs presented in Table 5. In the base case, it is assumed that 6.4 MW_{th} can be extracted from the cement plant to produced part of the steam required by the CO_2 stripper while the remaining part is produced by a natural gas boiler. It is worth noting that the steam cost presented in Table 5 accounts for both investments and operating costs of the steam production and that the costs associated with the steam consumption are reported in the results in the operating cost section.

All investment and operating costs are given in 2014 prices.

Finally, three key performance indicators (KPI) are used to compare the economic performances of the plant with and without capture:

1) The cost of cement (COC) evaluated as the annualized costs divided by the annual amount of cement produced;
2) The CO_2 capture cost evaluated as the increase in annualized costs of the cement plant with CO_2 capture divided with the amount of CO_2 captured as defined by Ho et al. [9];
3) The CO_2 avoided cost evaluated with the following equation, comparing the cost of cement and the equivalent specific emissions of the assessed cement plant and the reference cement plant without CO_2 capture.

$$\mathrm{CAC}=\frac{\mathrm{COC}-\mathrm{COC}_{\mathrm{ref}}}{(\mathrm{t}_{\mathrm{CO2}}/\mathrm{t}_{\mathrm{cement}})_{\mathrm{clk,eq,ref}}-(\mathrm{t}_{\mathrm{CO2}}/\mathrm{t}_{\mathrm{cement}})_{\mathrm{clk,eq}}}\qquad\left[\frac{€}{\mathrm{t}_{\mathrm{CO2}}}\right]$$

Table 5. Main assumptions for the economic analysis.

Financial assumptions	Cement plant without CO_2 capture	Cement plant with MEA-based CO_2 capture
CO_2 Capture Rate	0	0.90
Capacity factor , %	91.3	91.3
Tax rate, %	0	0
Operational life, years	25	25
Construction time, years	2	Cement: 2 / Capture: 3
Inflation rate, %	0	0
Discounted cash flow rate, %	8	8
CAPEX		
Total direct costs (TDC), $M€_{2014}$	149	228
Engineering, procurement, construction (EPC)	TDC*1.14	TDC*1.14
Total plant cost (TPC)	EPC*1.19	EPC*1.19
OPEX		
Raw meal, $€/t_{clk}$	5	5
Coal price, $€/GJ_{LHV}$	3	3
Natural gas price, $€/GJ_{LVH}$	-	6
Price of electricity, $€/MWh_{el}$	58.1	58.1
Cost of the steam produced from a natural gas boiler, $€/MW_{th}h$	-	25
Cost of the steam produced from the cement plant waste heat, $€/MW_{th}h$	-	7*
Carbon tax, $€/t_{CO2}$	0	0
Cooling water cost, $€/m^3$	-	0.39
Other variable O&M, $€/t_{cement}$	0.8	0.8
Insurance and loc. Tax, % TPC	2	2
Maintenance cost (including maintenance labor), % TPC	2.5	2.5
Cost of labor per person – k€/year	60	60
Operating labor - N° of persons	100	140
Maintenance labor cost, % Maintenance	40	40
Administrative labor cost, % O&M labor	30	30

** Based on the cost of a waste heat recovery unit combined with high temperature filter to handle the dusty stream.*

The results of the cost evaluation† for the case without and with MEA-based CO_2 capture are presented in Table 6 with the share of the different contributors to the cement cost. A total cost of cement of 45 $€/t_{cement}$ has been calculated for the case without CO_2 capture, while the case with MEA-based CO_2 capture is evaluated to 81 $€/t_{cement}$ at 0.90 CO_2 capture rate (CCR). This results in a CO_2 captured and avoidance costs of respectively 83 $€/t_{CO2,avoided}$. The results shows that the increase in the cost of cement when considering CO_2 capture is mainly linked to the increase in operating costs as the steam and electricity costs represent respectively 40 and 11% of the increase. On the other hand, the investment and fixed operating costs account for respectively 24 and 18% of the increase.

The total cost calculated in this work is lower than the 51.4 $€/t_{cement}$ reported by IEAGHG [8] for the case without CO_2 capture. The main reasons for this difference are the higher capacity factor assumed in the CEMCAP project (91.3%, vs. 80%), leading to lower CAPEX and fixed OPEX per ton of cement in CEMCAP, and the lower price of electricity assumed in CEMCAP (58.1 €/MWh vs. 80 €/MWh). The higher cost of electricity, however, benefits to cases where power is generated in addition to steam (coal or gas CHP). Indeed, in such cases, the high expected revenues from the electricity sales decrease the internal cost of steam required for the CO_2 capture. Comparatively, this results in higher cement and CO_2 avoided costs for the cases with CO_2 capture in this report than reported by IEAGHG [8]. To further illustrate this and the importance of steam supply source, the impact of the steam supply on the cost performances of the cement plant with CO_2 capture are investigated in section 4.2.

† It has to be highlighted that this value does not include the contribution of freights, transport, re-naturation of quarries etc.

Table 6. Operating, fixed and capital costs associated to the cement plant without and with MEA-based CO_2 capture.

Cost of cement [€/tcement]	Cement plant without CO_2 capture	Cement plant with MEA-based CO_2 capture
CO_2 capture rate	0	0.90
Raw meal	3.68	3.68
Fuel	6.92	6.92
Electricity	5.64	9.69
Steam	-	14.19
Carbon tax	-	0.00
Cooling water	-	0.65
Other variable costs	0.80	2.32
Variable OPEX	**17.03**	**37.44**
Operative, administrative and support labor	6.40	9.03
Insurance and local taxes	3.08	4.72
Maintenance cost (including maintenance labor)	3.85	5.90
Fixed OPEX	**13.33**	**19.64**
CAPEX	**14.99**	**23.60**
Cost of cement	**45.3**	**80.7**
CO_2 captured cost [€/$t_{CO2,captured}$]	**-**	**63.2**
CO_2 avoided cost [€/$t_{CO2,avoided}$]	**-**	**83.2**

4.2. The importance of steam supply

In order to evaluate the impact of the steam supply, seven steam supply/cost scenarios are compared. The first scenario correspond to the base case in which the 6.4 MW_{th} can be extracted from the cement plant while the remaining steam is produced from a natural gas boiler. The second and third scenario are based on the first one and considers different amount of waste heat which can be recovered from the cement plant. In the second scenario it is assumed that no waste heat is extracted, and in the third scenario it is assumed that 30% of the steam required can be generated by heat recovery from the cement plant, and this scenario is select to be approximate the Norcem cement plant case [10]. The fourth and fifth scenario considers that the steam required by the capture process can be extracted prior the low pressure turbine from a nearby power plant. In this case the steam cost and climate impact are based on the electricity that would have been produced from the steam, and two electricity prices are considered (58.1 and 80 €/MWh). Finally, the two last scenarios are based on a natural gas combined heat and power plant (CHP) considering two electricity prices (58.1 and 80 €/MWh). Indeed, as previously explained, the electricity price have a significant impact on the steam cost from a CHP plant. It is worth noting that scenarios 4 to 7 consider the 6.4 MW_{th} steam generation by waste heat from the cement plant.

Table 7 presents the steam and cost of the seven scenarios while Table 8 summarizes the steam cost and climate impact depending on the steam source.

Table 7. Steam cost and climate impact of the seven scenarios considered

Scenario	Steam supply	Average steam cost (€/MW_{th}h)	Average steam climate impact (kg_{CO2}/MW_{th}h)
Scenario 1 (base case)	Natural Gas boiler and 7% from waste heat recovery	24	191
Scenario 2	Natural Gas boiler and 0% from waste heat recovery	25.3	205
Scenario 3	Natural Gas boiler and 30% from waste heat recovery	19.8	144
Scenario 4	Extracted prior of LP Steam turbine [11][‡] (electricity price 58 €/MWh) and 7% from waste heat recovery	13	166
Scenario 5	Extracted prior of LP Steam turbine (electricity price 80 €/MWh) and 7% from waste heat recovery	17.7	166
Scenario 6	Natural gas CHP plant (electricity price 58 €/MWh) and 7% from waste heat recovery	26.1	190
Scenario 7	Natural gas CHP plant (electricity price 80 €/MWh) and 7% from waste heat recovery	3.7	190

Table 8. Steam cost and climate impact depending on the steam source

Steam source	Steam cost (€/MW_{th}h)	Steam climate impact (kg_{CO2}/MW_{th}h)
Waste heat available on the plant	7	0
Natural gas boiler	25	205
External coal power plant, electricity cost 58 €/MWh	13.5	178
External coal power plant, electricity cost 80 €/MWh	18.5	178
Natural gas CHP, electricity cost 58 €/MWh	27.5	205
Natural gas CHP, electricity cost 80 €/MWh	3.5	205

The results of the steam study are shown in Figure 3. The results show that if 30% of the steam required by the CO_2 capture can be extracted from the cement plant, similarly to the Norcem case, the CO_2 avoided cost can be reduced by 14% compared to the base case. On the other hand, if the steam can be extracted from a nearby power plant, the evaluation shows that the CO_2 avoided cost can be reduced by 22% when the electricity price is 58 €/MWh and by 14% when the electricity price is 80 €/MWh. However, it is worth noting that cases in which an external coal power plant is located nearby the cement plant may not be common. Finally, the scenarios based on a natural gas CHP plant has also the potential to decrease the CO_2 avoided cost by 35% if the electricity produced by the CHP plant can be sold at 80 €/MWh and offsets the steam production cost. However, it may not be very likely that such high electricity prices can be obtained and therefore this case is not very likely. Nevertheless, it also shows the importance that the electricity prices can have on the steam cost and therefore the economic performances of the plant with CO_2 capture.

As previously illustrated by Husebye and al. [12], the evaluation therefore shows that the steam supply source and electricity price has a significant impact on the CO_2 avoided cost and cost of cement. This highlights that the specific opportunities for steam supply at the cement plant, and more generally for CO_2 capture from industrial sources can have a significant impact on the CO_2 avoided cost. In addition, these results also emphasizes the importance of taking into account the different steam supply scenarios when comparing solvent based CO_2 capture technologies to emerging technologies such as membrane or low-temperature capture which do not require steam.

[‡] The cost and climate impact of the steam extracted prior the LP turbine are estimated considering that it could have been used to produce electricity. The cost and climate impact are therefore back calculated from the electricity cost and climate impact considering an efficiency of 23.3% .

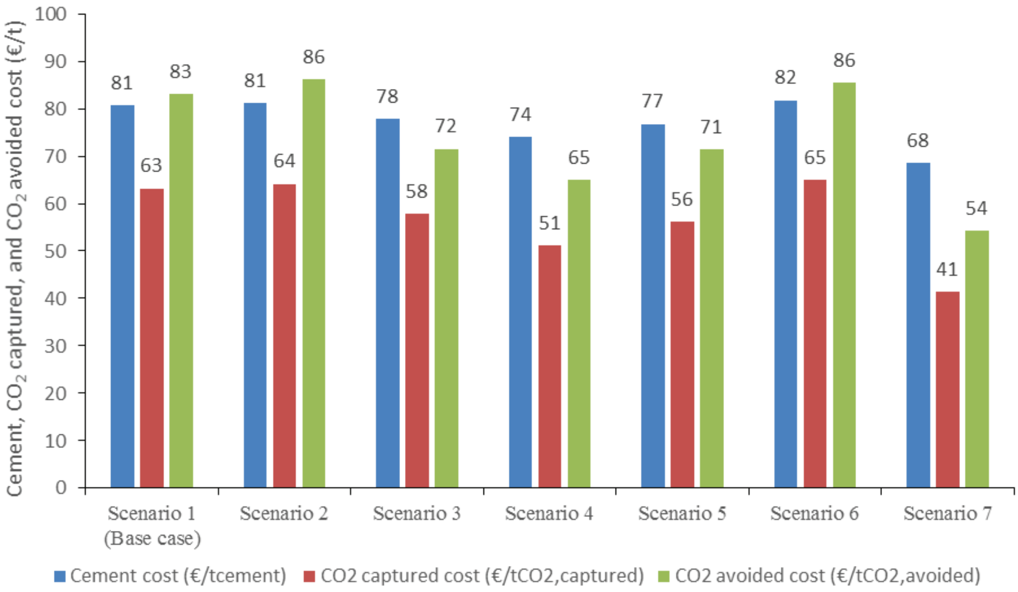

Figure 3: Cement plant cost, CO_2 captured cost and CO_2 avoided cost depending on the steam supply scenario.

5. Conclusions

This paper present the techno-economic assessment of an MEA-based CO_2 capture from a cement plant and the importance of the steam supply on the costs. The evaluations present the energy performances of the CO_2 capture process based on a cement plant with a clinker capacity of 3,000 t/d.

The cost evaluation lead to a cost of cement of 45 €/t_{cement} without capture, while the cost of cement with CO_2 capture is estimated to 81 €/t_{cement} in the base case in which steam is produced from cement plant waste heat and a natural gas boiler. This increase in cement cost is mainly due to the steam consumption and additional investments, and results in a CO_2 avoided cost of 83 €/$t_{CO2,avoided}$.

As the steam consumption accounts for close to half of the CO_2 avoided cost, the impact of six alternative steam supply scenarios are considered. The evaluations show that the CO_2 avoided cost can decrease by up to 35% depending on the steam supply and electricity price. However the possibility of these steam supply alternatives are specific to the considered cement plant, emphasizing therefore that CO_2 avoided cost from cement shall rather be given as a range depending on the steam supply than as a unique value as often illustrated in the literature. In particular, this becomes even more critical when comparing steam and non-steam intensive technologies for CO_2 capture from cement and industry.

Acknowledgements

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References

[1] Jordal K, Størset S, Røkke N. CEMCAP CO2 capture from cement production. 8th Trondheim Conference on CO2 Capture, Transport and Storage. Trondheim, Norway. 16-18 June 2015.
[2] Anantharaman R, Bolland O, Booth N, Dorst EV, Ekstrom C, Franco F, et al. D4.9 European best prectice

guidelines for assessment of CO2 capture technologies. DECARBit Project; 2011.
[3] Rao AB, Rubin ES, Keith DW, Granger Morgan M. Evaluation of potential cost reductions from improved amine-based CO2 capture systems. Energy Policy. 2006;34:3765-72.
[4] Roussanaly S, Anantharaman R, Lindqvist K, Zhai H, Rubin E. Membrane properties required for post-combustion CO2 capture at coal-fired power plants. Journal of Membrane Science. 2016;511:250-64.
[5] Schorcht F, Kourti I, Scalet BM, Roudier S, Sancho LD. Best Available Techniques (BAT) Reference Document for the Production of Cement, Lime and Magnesium Oxide: Industrial Emissions Directive 2010/75/EU:(Integrated Pollution Prevention and Control). European Commision. 2013.
[6] Spliethoff H. Power generation from solid fuels. Springer-Verlag Berlin Heidelberg, Berlin, Heidelberg, Germany. 2010.
[7] Barker D, Holmes D, Hunt J, Napier-Moore P, Turner S, Clark M. CO2 capture in the cement industry. 2008.
[8] Koring K, Hoening V, Hoppe H, Horsch J, Suchak C, Klevenz V, et al. Deployment of CCS in the Cement industry. 2013.
[9] Ho MT, Allinson GW, Wiley DE. Comparison of MEA capture cost for low CO2 emissions sources in Australia. International Journal of Greenhouse Gas Control. 2011;5:49-60.
[10] Jakobsen J, Roussanaly S, Anantharaman R. A techno-economic case study of CO2 capture, transport and storage chain from a cement plant in Norway. Submitted to Journal of Cleaner Production. 2016.
[11] Göttlichter G. The energetics of carbon dioxide capturein power plants. National Energy Technology Laboratory; 2004.
[12] Husebye J, Brunsvold AL, Roussanaly S, Zhang X. Techno economic evaluation of amine based CO2 capture: impact of CO2 concentration and steam supply Energy Procedia. 2012;23:381-90.