16th International Conference on Greenhouse Gas Control Technologies, GHGT-16

23rd -27th October 2022, Lyon, France

# Assessing Heat Pumps as Heat Supply Option for Solvent Regeneration in Cement Plants with Post-Combustion $CO_2$ Capture: Heat Integration, Energy Performance and $CO_2$ Emissions

Edoardo De Lena[a], Maurizio Spinelli[a], Antonio Conversano[a,b], Matteo C. Romano[b], Manuele Gatti[b]*

*[a] LEAP s.c.a.r.l, via Nino Bixio 27C, 29121 Piacenza, Italy*
*[b] Politecnico di Milano, Department of Energy, via Lambruschini 4, 20156 Milano, Italy*

## Abstract

In this work, the performance of a cement production plant retrofitted with a mono-ethanol amine (MEA) solvent-based post-combustion capture process are simulated, comparing three different heat supply options for solvent reboiling. Considering the limited waste heat available in the cement plant, particular attention has been given to the heat integration between the two processes. In particular, in this work, the following heat supply options are analyzed with detailed process simulations involving the whole cement plant, the $CO_2$ capture system and the heat generation unit:

- Natural gas-fired boiler without $CO_2$ capture from natural gas flue gases;
- Natural gas-fired boiler with $CO_2$ capture from natural gas flue gases;
- Electric-driven high temperature Heat Pump, integrated with the waste heat recoverable from the cement plant and CCS system (compressor and solvent coolers).

For these three configurations, two MEA plant designs are analyzed: (i) the baseline MEA process and (ii) the Lean Vapor Recompression (LVR). From the analysis conducted, it can be concluded that the LVR configuration allows primary energy savings of 5% and 11%, depending on the heat supply option considered. Moreover, considering the equivalent $CO_2$ emissions, which is the sum of Scope 1 (direct $CO_2$ emissions at stack) and Scope 2 ($CO_2$ emissions for electricity production taken from the grid, considering a carbon intensity of 268.6 $kg_{CO2}/MWh_e$), the case with heat pump achieves a $CO_2$ avoidance rate of 71-73% at current $CO_2$ intensity of electricity, while the case with natural gas boiler achieves a reduction of 65-69%, even though in the latter configuration the cement facility directly releases much more $CO_2$. Finally, the case with natural gas boiler with $CO_2$ capture achieves both the largest direct emission reductions (about 88%) and the highest $CO_2$ avoidance rates (80-81%). The analysis also shows that the breakeven $CO_2$ intensity of the electric grid between MEA with natural gas boiler but without $CO_2$ capture and MEA with heat pump is close to 378 $kg_{CO2}/MWh_e$, for which both systems show a reduction in equivalent $CO_2$ emission of about 65%. If electricity carbon intensity reduces below ~50 $kg_{CO2}/MWh_e$, the heat pump system is environmentally preferable with respect to the natural gas boiler case with $CO_2$ capture.

---

* Corresponding author. *E-mail address:* manuele.gatti@polimi.it

*Keywords:* Cement; Clinker; CCS; post-combustion CO2 capture; Heat Pump; Retrofit, MEA, Lean Vapour recompression

## 1. Introduction

Nowadays, it is estimated that the cement industry is responsible for around 8% of the global anthropogenic $CO_2$ emissions [1]. As about 60% of the emissions, corresponding to about 1.5 $Gt_{CO2}$/y [2], derives from the calcination of carbonates in the raw meal used for clinker production processes, Carbon Capture and Storage (CCS) is essential to achieve considerable emission reductions [3–5]. Solvent-based $CO_2$ capture systems are currently close to commercial readiness in cement plant [3,6–9] and are among the most mature post-combustion capture technologies, which can be retrofitted to existing cement plants, as they do not interfere with the clinker production process. A major drawback of amine based capture is their high heat demand, combined with the limited waste heat availability in cement plants, that makes heat supply the main cause for low energy efficiency and high $CO_2$ avoidance cost [10,11]. For this reason, when retrofitting a cement plant with a solvent-based CCS unit, the analysis of the heat integration potential and alternative steam generation options is of primary importance. In previous benchmarking studies [10], such heat is assumed to be provided by the combustion of natural gas in a dedicated boiler, which is the least capital intensive option. However, unless the $CO_2$ from the boiler is also captured, this leads to additional emissions, reduced overall $CO_2$ avoidance rates (in the range 60-70% when both Scope 1 and Scope 2 emissions are considered) and increased Specific Primary Energy Consumption for $CO_2$ Avoidance (SPECCA) compared to other $CO_2$ capture technologies (e.g. oxyfuel, Calcium looping, etc.) [10]. In order to reduce the thermal power consumption related to solvent regeneration in the stripper, and thus increase the overall energy performance of the system, several configurations have been presented in the literature in recent years, including the Stripper Overhead Compression (SOC) and Lean Vapor Recompression (LVR) configurations [12–15]. All these alternative configurations are based on the conversion of mechanical power into heat supplied directly to the stripper and they reduce direct fuel consumption but increase the electricity consumption of the system. A third alternative to avoid additional fuel consumption is to supply the solvent regeneration duty via a heat pump, possibly exploiting the relative low-temperature waste heat available in the system, but considerably increasing the electricity consumption.

In this work, two different options for heat supply options based on natural gas boiler and heat pump were analyzed from an energy and environmental point of view. In order to reduce the overall $CO_2$ emissions, the NG-boiler case was also assessed including post-combustion $CO_2$ capture from the boiler flue gases. These three heat supply options have been assessed for the following two MEA plant configurations: (i) Baseline case, where the stripper is designed with conventional reboiler and condenser and (ii) LVR, where the reboiler is partially replaced by a vapor compressor acting on the vapor stream generated by flashing the lean solvent from the stripper.

**Nomenclature**

| | |
|---|---|
| CCS | Carbon Capture System |
| DCC | Direct Contact Cooling |
| GWP | Global Warming Potential |
| LVR | Lean Vapour Recompression |
| MEA | Mono-Ethanol Amine |
| NG | Natural Gas |
| RES | Renewable Energy Sources |
| SPECCA | Specific Primary Energy Consumption for $CO_2$ avoided |
| TRL | Technology Readiness Level |

## 2. Plant description

The cement plant chosen as reference in this work is a modern cement plant with a clinker production capacity of about 1 $Mt_{clk}$/year and characterized by an annual Scope-1 $CO_2$ emission of about 0.86 $Mt_{CO2}$/year. The reference cement plant consists of a 5-stage cyclone preheater, a pre-calciner, where about 92% of the calcination takes place, a rotary kiln and a grid clinker cooler. This configuration is in line with the best available technology guidelines [16] and has been described in previous works [17,18]. As shown in Figure 1, the MEA-based system was placed between the gas-conditioning tower and the mill, which avoids $CO_2$ dilution due to air infiltration.

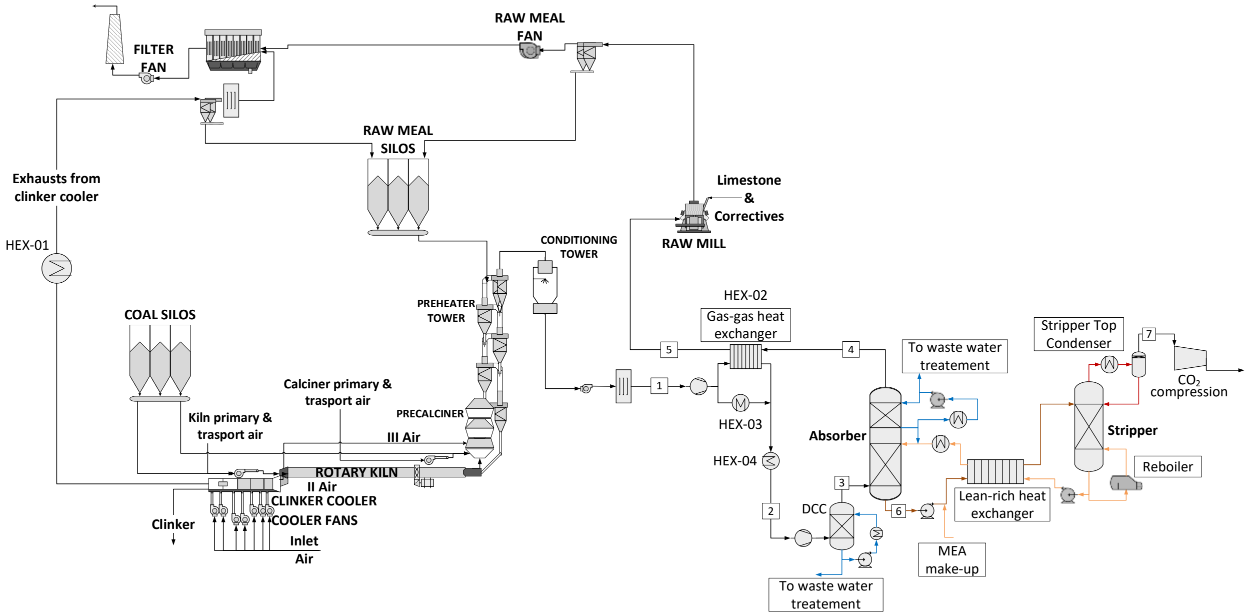

*Figure 1 - Schematic of cement plant with MEA-based system and (right) detail of MEA-based system*

Flue gases leaving the conditioning tower and the filter (#1) are divided into two streams: about 60% of the flow is sent to a regenerative heat exchanger (HEX-02) to heat the $CO_2$-lean gas up to 223°C for the drying process in the mill; the remaining part is cooled down to 160°C in HEX-03 to produce steam at 140°C for the reboiler. Before entering the direct contact cooler (DCC), the gases are cooled in HEX-04 to 60°C via either heat recovery (heat pump case) or cooling water. The flue gases at 60°C (#2) are pressurized by a dedicated fan and fed to the DCC where they are cooled down to 40°C. The gases (#3) are then sent to the adiabatic absorber at 40°C, where 90% of the $CO_2$ is captured. The $CO_2$-rich solvent (#6) is regenerated in a stripper at 2 bar with a reboiler temperature of around 122°C (solvent lean loading set to 0.24 $mol_{CO2}/mol_{alk}$). The captured $CO_2$ (#7) is then sent to the intercooled compression line and pressurized to 40 bar, while the $CO_2$-lean gases (#5) are heated up to 223°C and sent to the raw mill.
Figure 2 shows the cumulative temperature- waste heat diagram of the overall plant (i.e. cement + $CO_2$ capture unit) from which it can be seen that approximately 8 $MW_{th}$ are readily available for the production of saturated steam at 140°C. A fraction of the residual waste heat is used in a heat pump (evaporator working at 50 °C and condenser producing saturated steam at 140 °C) recovering heat from the available hot sources (HEX-04, stripper top condenser and, where needed, $CO_2$ compressor intercoolers) at temperatures greater than 60°C, with a COP (Coefficient of Performance) of 1.6 [19].

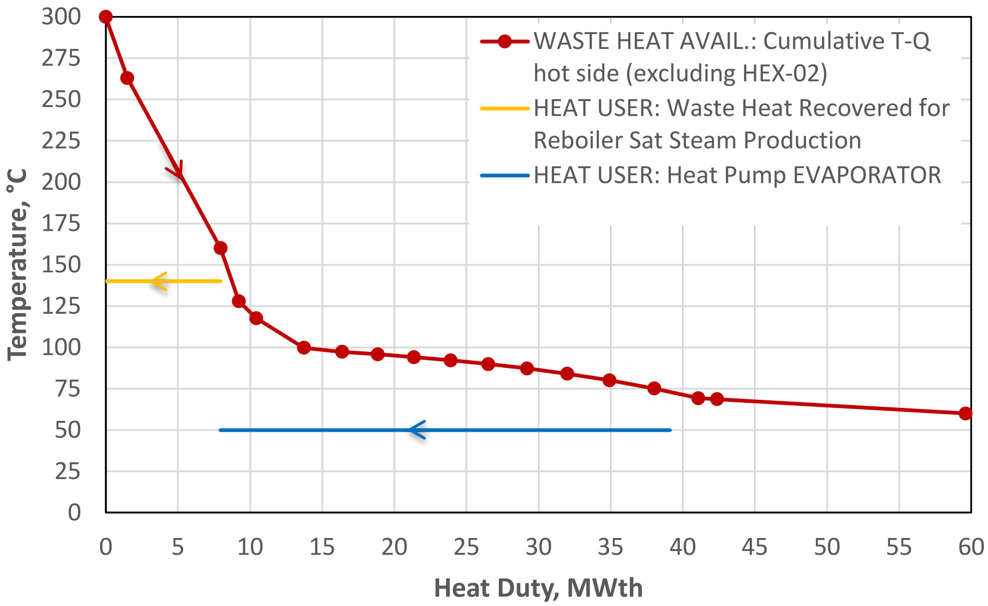

*Figure 2 - Cumulative T-Q diagram of whole cement and capture plant for the base configuration.*

The configuration described above ("Base configuration") is analyzed for both the heat supply options (natural gas boiler and heat pump). When the $CO_2$ from the natural gas boiler is captured, the boiler flue gas (#1b in Figure 3) is mixed with the cement plant off-gases and fed to the $CO_2$ capture plant. In Figure 3 the two configurations considered for the MEA system are shown, namely:

- *Base configuration*, where the stripper is equipped with a top condenser and a bottom reboiler, as in a standard configuration commonly proposed in the literature;
- *LVR configuration*, where the lean solvent extracted from the bottom of the stripper is flashed at a lower pressure (pressures ranging from 0.6 to 1.4 bar are preliminary investigated in this work) to produce a vapor stream (rich in steam, with minor amounts of $CO_2$ and MEA) and a liquid phase consisting in the lean solvent actually recirculated to the absorber. The vapor stream is compressed to 2 bar in a dedicated compressor and injected back to the stripper to support the stripping process. In this way, the stripper reboiler is partially replaced by a vapor compressor..

The aim of this work is to present an overall comparison from an energy-environmental point of view of all the configurations described above for the MEA system retrofitted to a modern cement plant. For the analyses conducted and presented in the following, the current Italian scenario (year 2019) for the $CO_2$ intensity of electricity consumption was taken as a reference, which is about 268.6 $kg_{CO2}/MWh_e$, For the energy analysis, the primary energy intensity of the electric mix is assumed equal to 1.18 $MJ_{LHV}/MJ_{el}$ (even though this parameter, which depends both on the fuel mix and on the efficiency of the electricity generation mix, may change significantly depending on the considered scenario, country and year as shown in Figure 4)

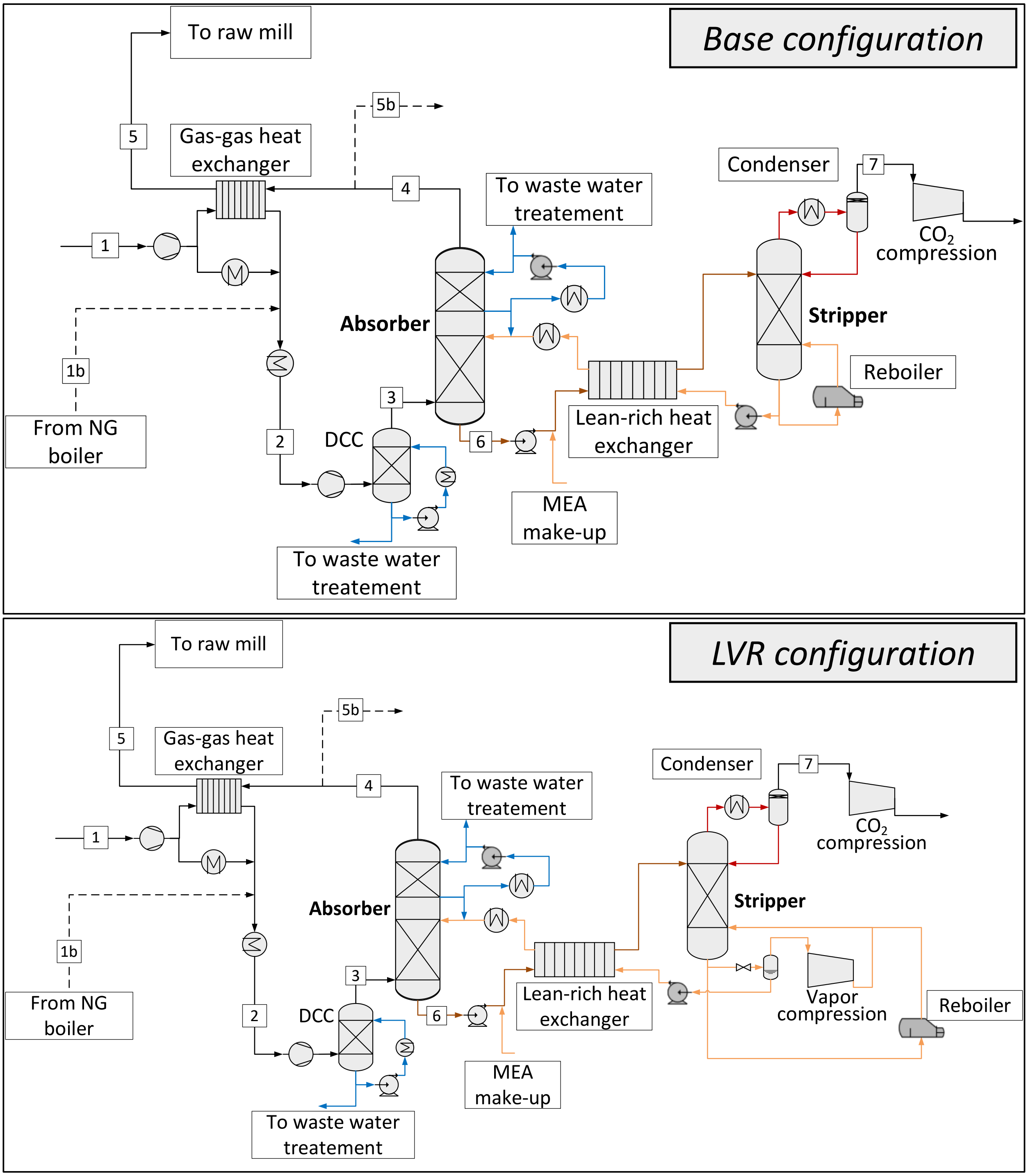

*Figure 3 - Schematics of the two MEA-system configurations considered in this work: (top) Base configuration, where the stripper is equipped with a condenser and a reboiler, and (bottom) LVR configuration, where the reboiler is partially repleced by a vapor compressor. The dotted lines (1b and 5b) are presented only for the cases with natural gas boiler and $CO_2$ capture from boiler flue gases.*

## 3. Results and discussions

The direct fuel consumption for clinker production in the reference cement is about 3.24 $GJ_{LHV}/kg_{clk}$, while the electricity consumption is about 131.6 $kWh_e/t_{clk}$, corresponding to a total primary energy consumption of about 943.2 $kWh_{LHV}/t_{clk}$. All configurations considered in this work show an increase in the primary energy consumption of the overall system.

For the LVR case, a parametric analysis has been conducted to understand the impact of different LVR flash pressures on the overall primary energy consumption of the capture process. Preliminary results, carried out for the case with $CO_2$ capture from NG boiler are shown in Figure 4, where each curve corresponds to a different assumption for the Electricity-to-Primary Energy ratio. In this work, a value of 1.18 $MJ_{LHV}/MJ_{el}$ has been adopted, while values between 3 and 4 are typical of power plant capture applications where steam is extracted from the steam turbine. The graph shows that, depending on the Electricity-to-Primary Energy ratio, the optimal flash pressure, from an energy standpoint, changes. In this work an LVR base case with flash pressure equal to 1 bar is selected, even though a more "aggressive" case featuring an LVR pressure of 0.6 bar could be also considered. The latter, although more promising in terms of energy efficiency is technically challenging since involves a compressor with outlet temperatures greater than 200 °C, which can be critical both for compressor feasibility and due to the increased solvent thermal degradation. A more detailed techno-economic assessment is therefore required to select the optimal case.

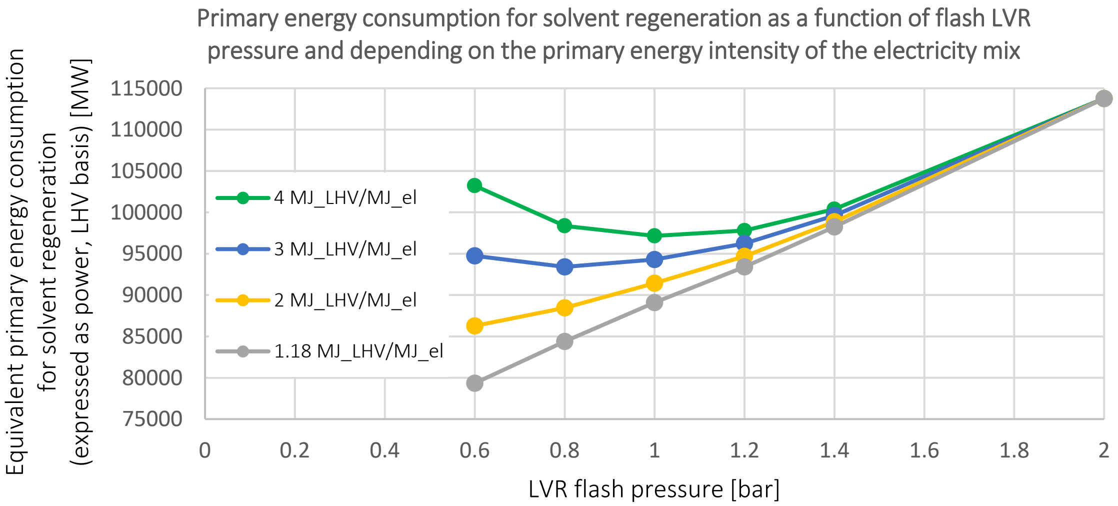

*Figure 4 – Effect of the LVR flash pressure and of the assumption on the Electricity-to-Primary Energy ratio on the equivalent primary energy consumption for solvent regeneration.*

As shown in Figure 5, where the breakdown of the total primary energy consumption is depicted, the Base case with natural gas boiler and $CO_2$ capture from boiler flue gases (low-emission boiler case) shows the highest primary energy consumption of about 2057 $kWh_{LHV}/t_{clk}$, of which about 47% is related to the natural gas required for MEA regeneration in the stripper reboiler.

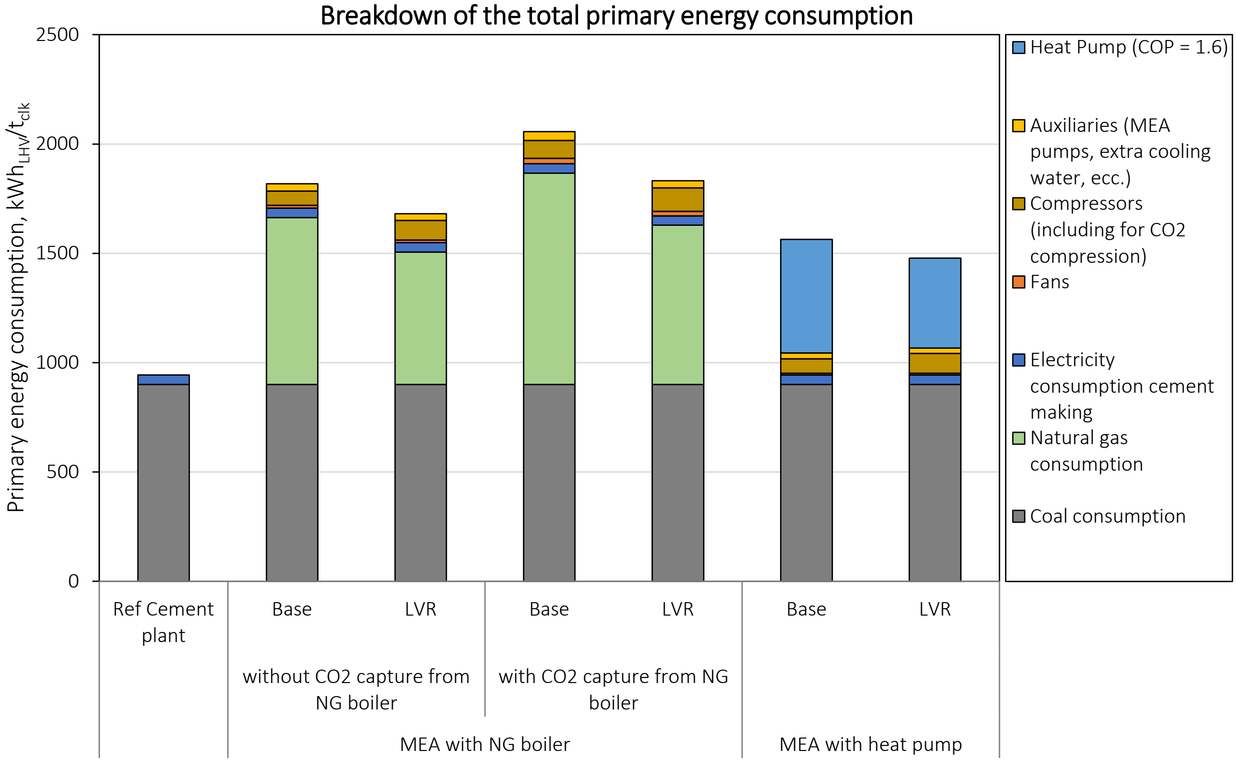

*Figure 5 - Breakdown of the total primary energy consumption for the different cases analyzed in this work.*

In the case with conventional natural gas boiler as heat supply system, the LVR configuration allows reducing the natural gas consumption by about 20.6% respect to the Base configuration, with an increase in electricity consumption of about 13.0%, resulting in an overall reduction in primary energy consumption of about 7.6%. In the case with low-emission boiler, the LVR configuration allows reducing the primary energy consumption by about 11.0% respect to the Base configuration (with a reduction in natural gas consumption of about 24.7% and an increase in electricity consumption of about 6.8%). In LVR configurations, the presence of a compression stage on the vapor at the bottom of the stripper allows all electricity to be converted into thermal energy required for solvent regeneration. Therefore, the vapor compression system is equivalent to a heat pump that converts electrical energy into useful thermal energy for the reboiler, with an equivalent COP (calculated as the ratio between the difference in reboiler heat demand for the Base and LVR configurations, and the electricity consumption in the vapor compressor) of about 7.04 for the case with conventional boiler and of about 9.03 for the case with low-emission boiler. On the other hand, the heat pump cases show the smallest increase in primary energy consumption due to capture: in the Base configuration with heat pump, the primary energy consumption is equal to 1563 kWh$_{LHV}$/t$_{clk}$, of which about 33.2% is related to the electricity consumption of the heat pump. Also in this option, the LVR configuration reduces the total energy consumption, resulting in a primary energy saving of about 5.4% compared to the Base configuration.
Figure 6 shows the breakdown of the total CO$_2$ emissions for the different cases.

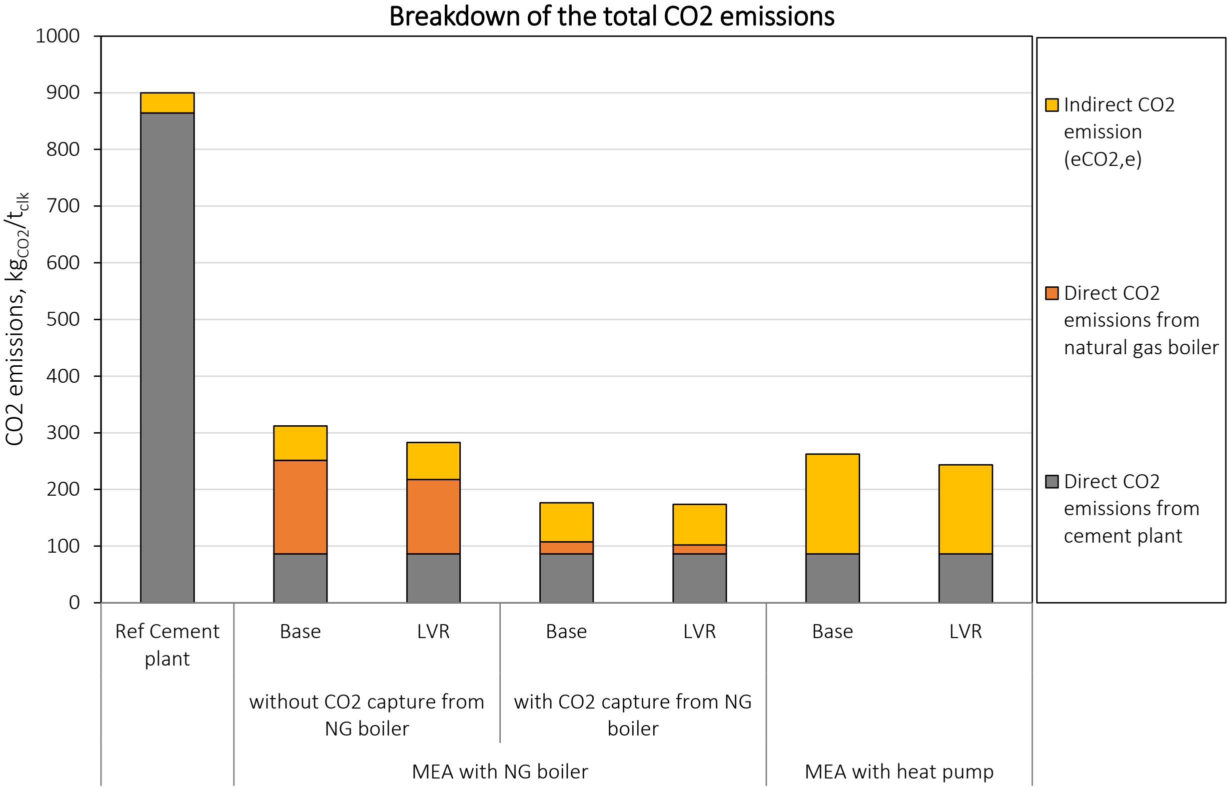

*Figure 6 - Breakdown of the $CO_2$ emissions for the different configurations analyzed in this work.*

The lowest Scope 1 (direct) $CO_2$ emissions are obtained in the cases based on heat pump, as heat generation via electricity does not involve any additional direct $CO_2$ emission. In contrast, configurations with conventional natural gas boiler result in the highest direct emissions because all the $CO_2$ generated in the natural gas boiler (orange bar in Figure 6) is emitted at the stack. Finally, cases with low-$CO_2$ emission boiler show slightly higher direct emission values than the heat pump case, because 90% of the $CO_2$ generated in both the cement plant and the boiler is captured in the MEA absorber. Considering the Scope 2 (indirect) $CO_2$ emissions (yellow bar in Figure 6) related to the consumption of electricity in the system, the heat pump configuration shows the highest values, due to the considerable increase in the electricity consumption of the system due to the heat pump. Oppositely, the cases with natural gas with conventional boiler are those with the lowest Scope 2 emissions. The sum of Scope 1 and Scope 2 emissions (equivalent $CO_2$ emissions) are minimum for the case with low-emission natural gas boilers, thanks to the lower Scope 1 emissions and the small increases in electricity consumption. As shown in Table 1, the cases with low-emission natural gas boiler have the highest $CO_2$ avoidance rates (around 80-81%), while the cases with conventional boiler have the lowest ones (around 65-69%), due to the large contribution of the CO2 generated from the boiler to Scope 1 emissions. In all cases, the LVR configurations show the lowest increases in primary energy consumption and the highest $CO_2$ avoidance rates.

*Table 1 – Heat and mass balances for the different cases analyzed in this work for the current Italian scenario.*

| | **Ref cement plant** | **MEA system with NG boiler** | | | | **MEA system with heat pump** | |
|---|---|---|---|---|---|---|---|
| | | **without $CO_2$ capture from NG** | | **with $CO_2$ capture from NG** | | | |
| | | **Base** | **LVR** | **Base** | **LVR** | **Base** | **LVR** |
| Direct fuel consumption, $GJ_{LHV}/tc_{lk}$ | 3.24 | 5.99 | 5.42 | 6.72 | 5.86 | 3.24 | 3.24 |
| Electricity consumption for cement making, $kWh_e/kg_{clk}$ | 131.6 | 131.6 | 131.6 | 131.6 | 131.6 | 131.6 | 131.6 |
| Additional electricity consumption for CCS, $kWh_e/kg_{clk}$ | 0.0 | 94.6 | 111.7 | 124.5 | 135.5 | 524.7 | 452.8 |
| Total electricity consumption cement making + CCS, $kWh_e/kg_{clk}$ | 131.6 | 226.2 | 243.3 | 256.1 | 267.1 | 656.3 | 584.4 |
| *$CO_2$ emissions* | | | | | | | |
| Scope 1 - Direct $CO_2$ emissions ($e_{CO2}$), $kg_{CO2}/t_{clk}$ | 864.3 | 251.4 | 217.5 | 107.5 | 102.2 | 86.2 | 86.4 |
| $CO_2$ Capture Ratio (direct emissions), - | - | 71% | 75% | 88% | 88% | 90% | 90% |
| *$CO_2$ intensity of electricity consumption: 268.6 $kg_{CO2}/MWh_e$* | | | | | | | |
| Scope 2 - Indirect $CO_2$ emission ($e_{CO2,e}$), $kg_{CO2}/t_{clk}$ | 35.3 | 60.8 | 65.3 | 68.8 | 71.7 | 176.3 | 157.0 |
| Scope 1 + 2 - Equivalent $CO_2$ emission ($e_{CO2,eq}$), $kg_{CO2}/t_{clk}$ | 899.7 | 312.2 | 282.8 | 176.3 | 173.9 | 262.5 | 243.4 |
| Scope 1 + 2 - $CO_2$ avoidance rate (equivalent emission reduction), - | - | 65.3% | 68.6% | 80.4% | 80.7% | 70.8% | 72.9% |
| *% RES share of Electr. Mix: 35%* | | | | | | | |
| *Net electric efficiency of ref. thermoelectric generation: 55%* | | | | | | | |
| Equivalent primary energy consumption, $kWh_{LHV}/t_{clk}$ | 943.2 | 1818.4 | 1680.7 | 2057.1 | 1831.8 | 1563.3 | 1478.3 |
| Equivalent primary energy consumption increase, - | - | 92.8% | 78.2% | 118.1% | 94.2% | 65.7% | 56.7% |
| SPECCA, $MJ_{LHV}/kg_{CO2}$ | - | 5.36 | 4.30 | 5.54 | 4.41 | 3.50 | 2.94 |

As for the SPECCA, despite the highest $CO_2$ avoidance rates, the configurations with low emissions boiler result in the cases with the highest SPECCA, due mainly to the increase in fuel consumption required to capture also 90% of the $CO_2$ generated from the boiler. In the low-emissions boiler case, the LVR configuration allows reducing the SPECCA of about 20.4% respect to the Base configuration (4.41 vs 5.54 $MJ_{LHV}/kg_{CO2}$). In contrast, the cases with heat pump show the lowest SPECCA, as a result of a more limited increase in equivalent primary energy consumption. Also in this case the LVR configuration achieves better performance compared to Base configuration, with a reduction in SPECCA of 16% (2.94 vs 3.50 $MJ_{LHV}/kg_{CO2}$). Finally, intermediate results for the SPECCA are obtained for cases with conventional natural gas boiler (5.36 $MJ_{LHV}/kg_{CO2}$ for the Base configuration and 4.30 $MJ_{LHV}/kg_{CO2}$ for the LVR configuration).

The results obtained are valid for the current Italian situation in terms of $CO_2$ intensity of the grid. Figure 7 shows how the $CO_2$ avoidance rate of the different systems considered in this work varies with the $CO_2$ intensity of the grid. For fully decarbonized grids, the cases with heat pumps are the best from the point of view of $CO_2$ equivalent emission reduction (Scope 1 + 2). For $CO_2$ intensity greater than 378 $kg_{CO2}/MWh_e$, cases with conventional natural gas boilers are favorable compared to those with heat pumps. On the other hand, cases with low-emission natural gas boilers are always favorable compared to the others already for $CO_2$ intensity values of around 49-53 $kg_{CO2}/MWh_e$ (depending on the configurations chosen), while for smaller values representative of a future scenario with a highly decarbonized grid the best solutions in terms of $CO_2$ avoidance rate are the configurations with heat pumps.

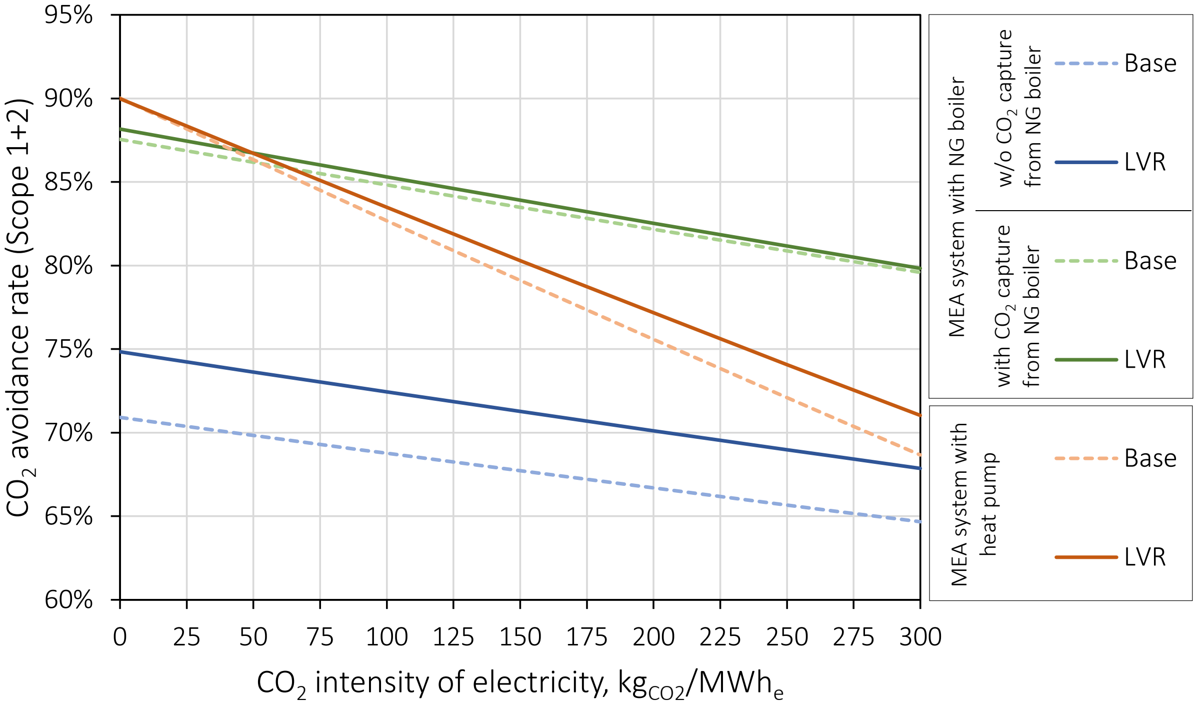

*Figure 7 - $CO_2$ avoidance rate as function of $CO_2$ emission factor of the electric grid: conventional natural gas boiler (blue), low $CO_2$ emissions boiler (green), and heat pump (orange).*

Finally, Figure 8 shows the trend of $CO_2$ avoidance rates, in the current Italian scenario of $CO_2$ intensity of electricity, for the different cases considered, as function of the supply chain natural gas leakage (expressed as a percentage of the natural gas used in the MEA capture system), considering a Global Warming Potential (GWP) value for methane of 29.8 $kg_{CO2}/kg_{NG}$. The cases with heat pump, not consuming natural gas, show constant value of $CO_2$ avoidance rates as natural gas leakage varies [20]. Both Base configurations show about 9% of reduction in $CO_2$ avoidance rate if a natural gas leakage of 3% is considered ($CO_2$ avoidance rate: ~59.2% for the case with conventional natural gas and ~72.7% for the case with low emission boiler), while LVR configurations show smaller reductions: about 7% for a natural gas leakage of 3% ($CO_2$ avoidance rate: ~63.7% for the case with conventional natural gas and ~74.9% for the case with low emission boiler).

If the same analysis from Figure 7 is updated including also a natural gas leakage of 1.5%, results show that the cases with heat pump become the best from the point of view of $CO_2$ emissions already for a $CO_2$ intensity of the grid between 134 and 142 $kg_{CO2}/MWh_e$, depending on the Base or LVR configuration considered. Above these threshold emission intensity factors, the best cases are those with low-emission boilers.

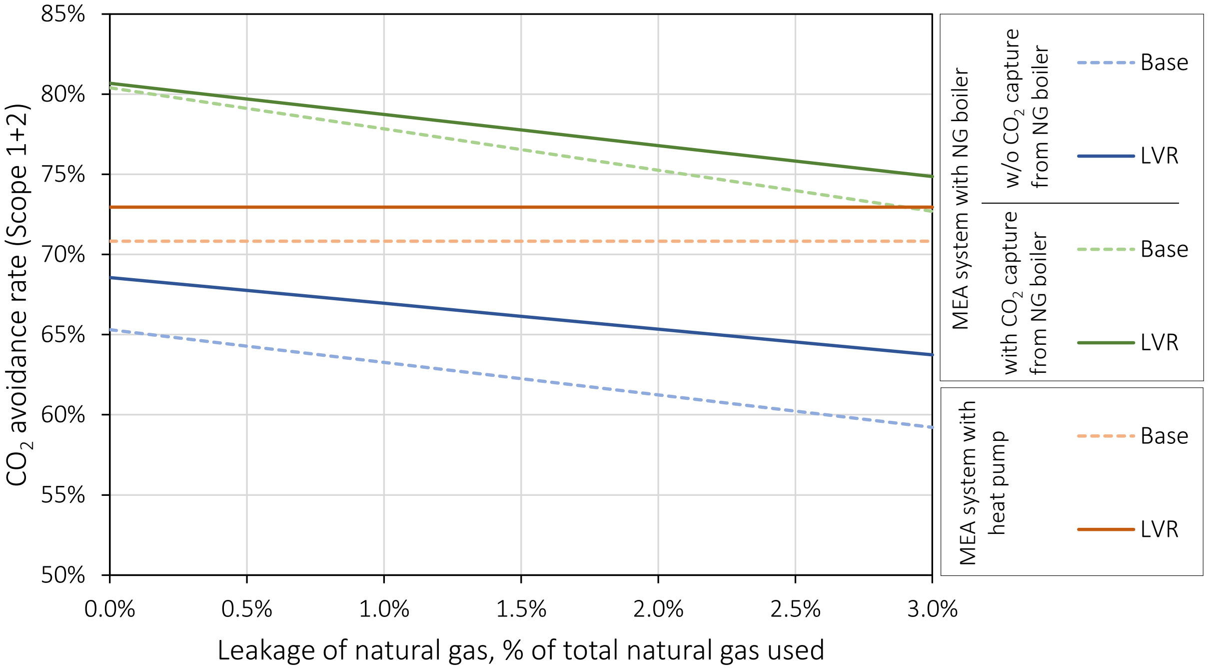

*Figure 8 - $CO_2$ avoidance rate as function of natural gas leakage (GWP=29.8 $kg_{CO2eq}/kg_{NG}$), considering the current Italian scenario for electricity production: conventional natural gas boiler (blue), low-emission boiler (green) and heat pump (orange).*

## 4. References

[1] Olivier JGJ, Janssens-Maenhout G, Muntean M, Peters JAHW. Trends in Global CO2 Emissions: 2016 Report. 2016.

[2] Andrew RM. Global CO2 emissions from cement production. Earth Syst Sci Data 2018. doi:10.5194/essd-10-195-2018.

[3] IEAGHG. Deployment of CCS in the Cement Industry. Ieaghg 2013.

[4] IEA. Technology Roadmap Low-Carbon transition in the Cement Industry. 2018.

[5] Cembureau. Cementing the European Green Deal. 2021.

[6] Choi J, Cho H, Yun S, Jang MG, Oh SY, Binns M, et al. Process design and optimization of MEA-based CO2 capture processes for non-power industries. Energy 2019;185:971–80. doi:10.1016/j.energy.2019.07.092.

[7] Roussanaly S, Fu C, Voldsund M, Anantharaman R, Spinelli M, Romano M. Techno-economic Analysis of MEA CO2 Capture from a Cement Kiln - Impact of Steam Supply Scenario. Energy Procedia, 2017. doi:10.1016/j.egypro.2017.03.1761.

[8] Dubois L, Thomas D. Comparison of various configurations of the absorption-regeneration process using different solvents for the post-combustion CO2 capture applied to cement plant flue gases. Int J Greenh Gas Control 2018. doi:10.1016/j.ijggc.2017.12.004.

[9] Garðarsdóttir SÓ, Normann F, Skagestad R, Johnsson F. Investment costs and CO2 reduction potential of carbon capture from industrial plants – A Swedish case study. Int J Greenh Gas Control 2018. doi:10.1016/j.ijggc.2018.06.022.

[10] Voldsund M, Gardarsdottir S, De Lena E, Pérez-Calvo J-F, Jamali A, Berstad D, et al. Comparison of Technologies for CO2 Capture from Cement Production—Part 1: Technical Evaluation. Energies 2019;12:559. doi:10.3390/en12030559.

[11] Gardarsdottir S, De Lena E, Romano M, Roussanaly S, Voldsund M, Pérez-Calvo J-F, et al. Comparison of

Technologies for CO2 Capture from Cement Production—Part 2: Cost Analysis. Energies 2019;12:542. doi:10.3390/en12030542.

[12] Jassim MS, Rochelle GT. Innovative Absorber/Stripper Configurations for CO 2 Capture by Aqueous Monoethanolamine 2006. doi:10.1021/ie050547s.

[13] Ahn H, Luberti M, Liu Z, Brandani S. Process configuration studies of the amine capture process for coal-fired power plants. Int J Greenh Gas Control 2013;16:29–40. doi:10.1016/J.IJGGC.2013.03.002.

[14] Oh HT, Ju Y, Chung K, Lee CH. Techno-economic analysis of advanced stripper configurations for post-combustion CO2 capture amine processes. Energy 2020;206:118164. doi:10.1016/J.ENERGY.2020.118164.

[15] Sanchez Fernandez E, Bergsma EJ, de Miguel Mercader F, Goetheer ELV, Vlugt TJH. Optimisation of lean vapour compression (LVC) as an option for post-combustion CO2 capture: Net present value maximisation. Int J Greenh Gas Control 2012;11:S114–21. doi:10.1016/J.IJGGC.2012.09.007.

[16] 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. 2013. doi:10.2788/12850.

[17] De Lena E, Spinelli M, Martínez I, Gatti M, Scaccabarozzi R, Cinti G, et al. Process integration study of tail-end Ca-Looping process for CO2 capture in cement plants. Int J Greenh Gas Control 2017;67:71–92. doi:10.1016/j.ijggc.2017.10.005.

[18] Campanari S, Cinti G, Consonni S, Fleiger K, Gatti M, Hoppe H, et al. Design and performance of CEMCAP cement plant without CO2 capture. CEMCAP Deliverable D4.1. www.sintef.no/projectweb/cemcap/results/ 2016.

[19] Arpagaus C, Bless F, Uhlmann M, Schiffmann J, Bertsch SS. High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials. Energy 2018;152:985–1010. doi:10.1016/j.energy.2018.03.166.

[20] Balcombe P, Anderson K, Speirs J, Brandon N, Hawkes A. The Natural Gas Supply Chain: The Importance of Methane and Carbon Dioxide Emissions. ACS Sustain Chem Eng 2017;5:3–20. doi:10.1021/ACSSUSCHEMENG.6B00144/ASSET/IMAGES/MEDIUM/SC-2016-00144C_0015.GIF.