Doctoral Dissertation
Doctoral Program in Energetics (36th Cycle)

# Towards net-zero $CO_2$ emissions in heavy industry

An energy, environmental, and economic analysis of Post-Combustion Carbon Capture application in the cement and steel industries

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# Summary

The decarbonization of heavy industries represents a very challenging and pressing issue for the transition to an environmentally sustainable energy system. Among these hard-to-abate industries, the steel and cement sectors are some of the most energy-intensive and $CO_2$-emitting, together accounting for around 10% of the global anthropogenic GHG emissions. Achieving low $CO_2$ emissions in these industrial processes will necessarily require the integration of innovative technologies into production plants. In this regard, Carbon Capture and Storage is expected to play a key role in the future energy transition, especially in mitigating $CO_2$ emissions from the steel and cement sectors.

Regarding these two hard-to-abate sectors, post-combustion carbon capture systems, specifically, can reduce both combustion and process-related $CO_2$ emissions, achieving large emissions reductions that are often unattainable with other techniques such as improvement in energy efficiency or fuel shift. Amine Scrubbing and Calcium Looping are two $CO_2$ capture systems receiving considerable attention for these applications. Amine Scrubbing has already reached the early commercial stage, while Calcium Looping is a more innovative technique particularly promising for large-scale applications. Notably, these gas separation technologies are themselves energy-intensive processes, meaning their adoption significantly impacts the energy and mass balance of production plants, increasing fuel demand and production costs.

One of the main goals of this research work is to analyze the integration of Calcium Looping into state-of-the-art cement and steel production plants, comparing and evaluating different integrated processes in terms of avoided emissions, energy consumption, and costs. A distinctive advantage of Calcium Looping is its cheap $CO_2$ sorbent, i.e. limestone, a material already widely used in the industry. This also enables the design of plant layouts characterized by a high degree of integration between the $CO_2$ capture unit and the production process, especially for cement applications. The environmental and economic performance of this technology is promising, with reductions in equivalent $CO_2$ emissions (including indirect $CO_2$ emissions due to electricity consumption) ranging from 64% to 84%, specific primary energy consumption of 3.7-6.6 MJ/$kg_{CO2,eq}$, and cost per equivalent $CO_2$ avoided estimated between 35 €/$t_{CO2,eq}$ and 79 €/$t_{CO2,eq}$ (excluding costs for $CO_2$ transportation and storage).

Calcium Looping can also be integrated with a concentrated solar system. In this configuration, the energy demand of the $CO_2$ separation process can be fully supplied by solar energy, avoiding additional fuel consumption and allowing for very high $CO_2$ emissions reduction between 91% and 96%. The estimated energy performance of the systems is also very promising, with specific primary energy

consumption per $CO_2$ avoided at 0.6-1.25 MJ/$kg_{CO2,eq}$. On the other hand, capturing $CO_2$ with solar calcium looping will require the installation of a large heliostat field and solid storage.

Notably, even with the high emissions reduction achievable, integrating post-combustion carbon capture into the production process is insufficient to reach net-zero $CO_2$ emissions. However, it can play a central role in combination with other decarbonization and emission mitigation techniques to achieve this goal. This work, therefore, also aims to analyze and evaluate Carbon Capture and Storage from a net-zero emissions perspective in the cement industry. In this regard, the integration of a state-of-the-art Amine Scrubbing $CO_2$ capture unit in the cement production process was also studied. Considering the scope of this analysis, environmental and economic performance was estimated with a cradle-to-gate system boundary, considering not only the emissions and energy consumption of the production plant but also the main upstream processes related to cement production. Carbon capture and storage can achieve a substantial reduction in the plant $CO_2$ emissions corresponding to approximately 70% of the cradle-to-gate GHG emissions of the production process.

$CO_2$ removal technologies will thus be needed to compensate for the few $CO_2$ vented at the plant stack and the upstream emissions. This can be achieved through Direct Air carbon Capture or with the combustion of alternative fuels characterized by a biogenic carbon content in the production process, such as biomass or refuse-derived fuels. In this regard, the combination of Post Combustion Carbon Capture and fuel shift to waste fuels is particularly promising as it can achieve net-zero and potentially even negative emissions even without the aid of Direct Air carbon Capture. Even this solution, however, results in a significant increase in the primary energy demand (+90%) and production costs (+55%) of the production process.