Superstructure optimization for a novel cement production process utilizing secondary raw materials

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Conventional cement production is an energy-intensive process and a major contributor to direct and indirect greenhouse gas (GHG) emissions. Direct GHG emissions arise from calcination of the limestone raw material and fossil fuel combustion, the latter being needed to provide process heat, especially for achieving the high temperatures required in the rotary kiln. Significant reduction in the global warming impact (GWI) of cement production requires implementing various carbon mitigation strategies, e.g., applying carbon capture technologies or using renewable fuels. However, to achieve climate and resource neutrality, utilization of secondary raw materials must be considered to close material cycles other than just the carbon cycle.

We propose a new route for a decentralized cement production using mineral secondary raw materials and producing an alternative cement clinker (belite cement clinker). The envisioned plant capacity is 50 kilotonnes of belite clinker per year. Using decentralized sources of secondary raw materials from concrete waste, we aim to replace a significant fraction of Portland cement clinker in standardized cement, thereby substantially reducing CO_2 emissions. In addition, the thermal energy supply is reduced compared to conventional Portland cement clinker, as the production of belite clinker requires a significantly lower temperature. To achieve carbon neutrality, the preliminary plant design must be complemented with carbon capture and utilization or storage (CCUS) technologies and an energy supply system based on renewable energies. To date, however, CCUS technologies in the cement industry have been studied separately and it is unclear which combination of technologies is most promising for the new route.

We follow a superstructure optimization approach to maximize process economics and minimize GWI by tailoring the use of CCUS technologies to the preliminary plant design. Our superstructure model incorporates recycled demolition material as feedstock and various CCUS technologies (unit operations) and possible interconnections between them. Specifically, it includes carbonation of minerals, e.g., coarse aggregates in concrete recycling, oxyfuel combustion, electricity- or fuel-powered rotary kiln, alkaline or polymer electrolyte membrane electrolysis, catalytic or biological methanation, as well as hydrogen, natural gas, or syngas as fuels for generating process heat. We implement the superstructure model in our open-source energy system optimization framework COMANDO and formulate and solve a bi-objective mixed integer linear program (MILP) to identify Pareto-optimal process designs, i.e., process configurations with minimal total annualized costs (TAC) and minimal GWI.

Analysis of the resulting optimal designs reveals that strong GWI reductions can be achieved but that the application of carbon capture and utilization technologies, e.g., power-to-gas, leads to higher electricity consumption and thus operating cost, compared to a baseline case of belite clinker production with an electric rotary kiln. Furthermore, to achieve promising trade-offs between minimum GWI and minimum TAC, the availability of electricity with low GWI is crucial. The superstructure approach can be used to study scenarios under which the production can become economically and ecologically viable by generating the corresponding optimal process designs.