Options for Achieving Carbon Neutrality in Cement Production: A Mixed-Integer Linear Programming Approach

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Abstract:

The cement industry is among the most carbon-intensive industrial sectors due to significant process-related CO_2 emissions, making its decarbonization essential for achieving climate-neutrality targets. This study develops a comprehensive mixed-integer linear programming (MILP) model to assess transformation strategies for an idealized cement plant aiming for net-zero CO_2 emissions. The model incorporates multiple process heat supply options, carbon capture technologies, CO_2 transport and sequestration via pipeline or railway (CCS), and carbon utilization through methanol synthesis (CCU). Biomass-based alternative fuels can help to reduce CO_2 emissions and even lead to net-negative CO_2 emissions. Results indicate that the distance between the cement plant and the sequestration site strongly affects the relative competitiveness of CCS versus CCU. In general, CO_2 transport via railway is preferred over pipeline transport. However, because of a maximum sequestration rate, the train's transport capacity was indirectly curtailed by its batch-wise operating mode. The choice of transport for sequestration also affects the cost-optimal carbon capture technology. Hereby, oxyfuel-based capturing was preferred when CO_2 transport via railway dominates. Depending on reasonable distances lower than $1000\,\mathrm{km}$, levelized costs of carbon capture, transport, and storage range between 77.17 and $228.93\,€/\mathrm{t}_{\mathrm{CO_2}}$. In scenarios allowing both CCS and CCU, the model focused on CCS for distances less than $1000\,\mathrm{km}$. Furthermore, net-negative CO_2 emissions were achieved regardless of the transport distance for CO_2 prices exceeding $200\,€/\mathrm{t}_{\mathrm{CO_2}}$. Methanolistion is only preferred for high transport distances, although a small share is still sequestrated via train-based CO_2 transport. When enforcing CO_2 neutrality via methanolisation, levelized costs amount to $667.92\,\mathrm{e}/\mathrm{t}_{\mathrm{MeOH}}$. The findings provide quantitative insights into cost-optimal decarbonization strategies for future cement production systems, demonstrating that net-negative CO_2 can be economically feasible.

Keywords:
Energy System Modeling, Cement Industry, Carbon Neutrality, Sequestration, Methanolisation.

1. Introduction

The European Union aims to become CO_2 neutral by 2050 [1]. For achieving these ambitious goals, the decarbonization of the cement industry is of high relevance. Today, the production of cement accounts for approximately $8\,\%$ of all anthropogenic CO_2 emissions, while production rates continue to increase [2]. Due to the fact that approximately $60\,\%$ of its direct emissions correlate to process emissions from the calcium carbonate decomposition, the decarbonization of the cement industry is particularly challenging [3]. The carbon intensity for the total global cement production varies between 0.832 and $1.075\,\mathrm{t}_{\mathrm{CO_2}}/\mathrm{t}_{\mathrm{clinker}}$ [4]. The exact pathway towards decarbonization is anything but clear yet, and there are multiple strategies and technologies, such as savings in clinker production, alternative fuels, or carbon capture and sequestration/utilization, currently being considered by the cement industry to make their contribution [5, 6, 7].

Many studies have already summarized potential decarbonization technologies, but only a few studies have presented modeling approaches for assessing a concrete transition towards carbon neutrality. For instance, Obrist et al. [8] present a model for projecting transition pathways of the cement industry in Switzerland employing a bottom-up optimization model based on the TIMES framework. Besides future reductions in specific energy consumption, the results indicate that a minimum CO_2 tax of $70\,€/t_{CO_2}$ is required for employing carbon capture technologies. Hereby, post-combustion amine-based scrubbers are preferred over oxyfuel-based technologies due to retrofitting options. However, the oxyfuel process shows a higher total energy efficiency. The authors did not cover subsequent options for CO_2 utilization. Williams, Yang, and Nhuchhen [9] compared different decarbonization pathways for fuel substitution, incorporating ASPEN Plus process simulations. The authors found that gas-fuelled oxyfuel combustion has the lowest total energy input, whereas hydrogen-based fuel systems have the highest CO_2 reduction potential. However, a full transition covering carbon capture options and thus, also eliminating process-based CO_2 emissions is missing. In contrast to this, Emanuelsson, Rootzén, and Johnsson [10] investigated the potential for implementing CCS for the cement industry on a European level by performing a bottom-up techno-economic assessment of the cost of CCS implementation. It was found that the key drivers influencing a successful transition of the European cement industry towards carbon neutrality are increasing CO_2 prices and sufficient CO_2 storage providers, highlighting the fact that the cement industry would require around $70\,\%$ of the currently announced CO_2 squestration potential in Europe indicating utilization conflicts with other sectors or industries. Also on a European scope, Cavalett et al. [4] assessed different decarbonization options for the cement industry, taking into account effects on climate change, water depletion, fossil fuel use, and human health. It was found that oxyfuel-based systems using alternative fuels and CO_2 sequestration provide the largest climate change mitigation benefits. In contrast to this, oxyfuel-based systems with CCU even lead to a negative climate change impact due to the process-based CO_2 emissions. Apart from that, thermal energy efficiency gains and a lower clinker-to-cement ratio can already significantly decrease environmental impact.
Even though these studies provide valuable insights on the transition of the cement industry towards CO_2 neutrality, a comprehensive bottom-up and site-specific optimization model for assessing energetic and process-based CO_2 reduction technologies, taking into account competing transformation paths, such as carbon capture and sequestration or utilization, is currently missing in the literature. Therefore, this study proposes a mixed-integer linear programming (MILP) approach for optimizing the transition costs of an ideal cement plant towards CO_2 neutrality. The model incorporates several options for process heat supply and carbon capture. Furthermore, different options for CO_2 transport to a potential sequestration site and the conversion of capture CO_2 to methanol, considering its biogenic and fossil carbon content. By forcing CO_2 neutrality, the levelized costs of carbon capture and transport, or the required revenue for the synthesized methanol, can be evaluated, and the impact of exogenous key assumptions, such as distance to the sequestration location or the CO_2 price, can be discussed.

2. Methodology

The energy system model is initialized with the Python for Power System Analysis (PyPSA) framework. PyPSA is an open-source toolkit specifically designed to simulate and optimize power and energy systems [11]. PyPSA builds on LinoPy, which enables the implementation of customized linear and MILP modeling constraints [12]. The model covers one representative year with hourly resolution, which is especially relevant when modeling technologies that are heavily influenced by electricity import costs, such as electrolysis or CO_2-based methanol synthesis. For solving the model, gurobi was used.

2.1. Modeling Setup and Key Assumptions

The main process steps within the cement production can be summarized as follows: After quarrying the raw material, crushing enables a homogeneous educt composition. Afterwards, the clinker is dried, preheated and burnt in the kiln system. The combination of the dry process, suspension preheater kiln, and precalcinator is the most established cement production process in the European Union. For the clinkerization process after the preheater and optional calcinator, a rotary kiln is typically used for the clinkerization process at a temperature of 1350 to $1500\,^{\circ}\mathrm{C}$. The exhaust gas typically leaves the kiln with a temperature of 90 to $150\,^{\circ}\mathrm{C}$. [13] This process step is by far the most relevant for modeling a cement plant since it accounts for $100\,\%$ of the thermal and $20\,\%$ of the electrical energy demands. Other sources for electrical energy demand are the grinding and cooling [13]. In this model, the different steps of clinker and cement production are not explicitly modeled. Instead, aggregated hourly electrical and thermal demands of cement production are implemented. A daily production capacity of $4000\,\mathrm{t_{Cement}/d}$ is assumed. A clinker factor of $0.59\,\mathrm{t_{clinker}/t_{cement}}$ [14] leads to a daily clinker production capacity of $2360\,\mathrm{t_{clinker}/d}$, which correlates to an hourly process heat demand of $63.52\,\mathrm{MWh_{th}}$ and $15.15\,\mathrm{MWh_{el}}$. Furthermore, the production capacity leads to $52.71\,\mathrm{t_{CO_2}/h}$ process-based emissions. Demands are assumed to be constant throughout the year.

The general model setup can be divided into two sections, as visualized in Figure 1 and 2. First, on the cement plant level (see Figure 1), the heat and electricity demands are implemented. Hereby, different technologies for providing the process heat are taken into account. These technologies incorporate hard coal, natural gas, and several alternative fuels with varying heating value and thus, varying maximum blending rates due to their moisture content. It is assumed that the coal-based furnace system is already installed, and to utilize natural gas or alternative fuels, the model must invest in retrofitting the oven system. Hereby, CAPEX and OPEX required for fuel switching are taken into account. The alternative fuel furnace system offers an additional degree of freedom: the option to buy five different alternative fuels. The five represented alternative fuels are plastic waste, waste oil, used tires, animal meal, and sewage sludge. For each fuel, an individual emission factor is defined, leading to the energy-based CO_2 emissions. Note that alternative fuels have a certain biogenic carbon share. Capturing and sequestrating these carbon sources can lead to net negative emissions. Furthermore, the process emissions are added to the total CO_2 emissions in the flue gas. The model can import electricity, and expansion of electricity storage is also possible, though its maximum storage capacity is limited. Also, onsite production for oxygen via an air separation unit and hydrogen via proton exchange membrane electrolysis (PEM), including its side product oxygen, is taken into account. It should be noted that H_2 must be produced onsite and cannot be imported to avoid modeling inconsistencies originating from H_2 and electricity import costs. CO_2 may be captured from the flue gas either by expanding a post-combustion amine scrubber or via oxyfuel-based combustion. For both capturing technologies, a $95\,\%$ capture rate is assumed. Otherwise, the CO_2 is emitted to the atmosphere, leading to a fee correlating with the CO_2 price. In the base case, the CO_2 price is assumed as $210\,€/\mathrm{t_{CO_2}}$. An onsite CO_2 storage tank can buffer fluctuating CO_2 capture rates, but with limited maximum capacity. As indicated by Figure 2, the processing options for captured CO_2 are either onsite CO_2-based methanol synthesis or sequestration. For the methanolisation, hydrogen and electricity are modeled as additional inputs. Again, the model can expand a methanol storage tank with limited capacity, depending on the methanol plant's production capacity. It should be noted that there is no specific demand for methanol. Instead, a revenue from selling the produced methanol is implemented. In the reference scenario, the revenue is $81\,€/\mathrm{MWh_{MeOH}}$, which corresponds to the market value of fossil methanol in 2023 [15]. Methanol cannot be exported continuously, but only once per day. The amount of sold methanol may not vary over the year. However, it is possible not to sell any methanol for selected days. In contrast to this, for modeling the sequestration of CO_2, two transport technologies, i.e. transport via pipeline and transport via railway, are considered. For CO_2 transport via railway, the CO_2 needs to be liquified onsite. Note that amine-based capturing plants provide dense CO_2, whereas the oxyfuel-based capturing plant already incorporates CO_2 liquification. The additional energetic demands and investment costs for converting captured CO_2 to either state are accounted for accordingly. Furthermore, it is assumed that the train leaves the cement plant once per day with a maximum capacity of $2200\,\mathrm{t_{CO_2}}$. Alternatively, for dense CO_2 transport via pipeline, a minimum extendable capacity of $0.06\,\mathrm{Mt_{CO_2}/a}$ is implemented [16]. It is assumed that the CO_2 is transported to the North Sea, from where it is permanently sequestrated. First, the CO_2 is transported to a CO_2 terminal, which incorporates a CO_2 buffer tank. From there, another pipeline leads to the final near-shore CO_2 reservoir. Again, minimum extendable capacities for the terminal and the near-shore CO_2 reservoir are taken into account. To be align with the techno-economic data of [16] the maximum injection capacity is curtailed to $500\,\mathrm{t_{CO_2}/h}$. In the base case, the distance between the cement plant and the CO_2 terminal is assumed as $500\,\mathrm{km}$. Pipeline transport furthermore requires expansion of pumping stations every $100\,\mathrm{km}$. It should be noted that the expansion of the transport infrastructure follows a greenfield approach. Therefore, sequestration costs cover transport infrastructure, the CO_2 terminal, and the sequestration itself.

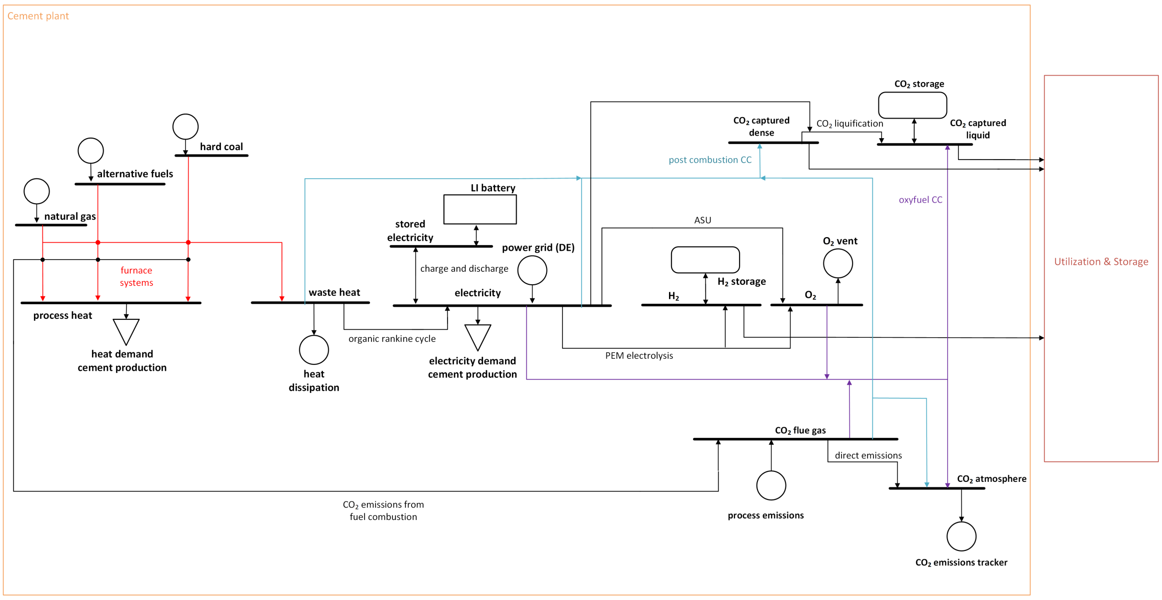

Figure 1: Implementation setup of the idealized cement plant.

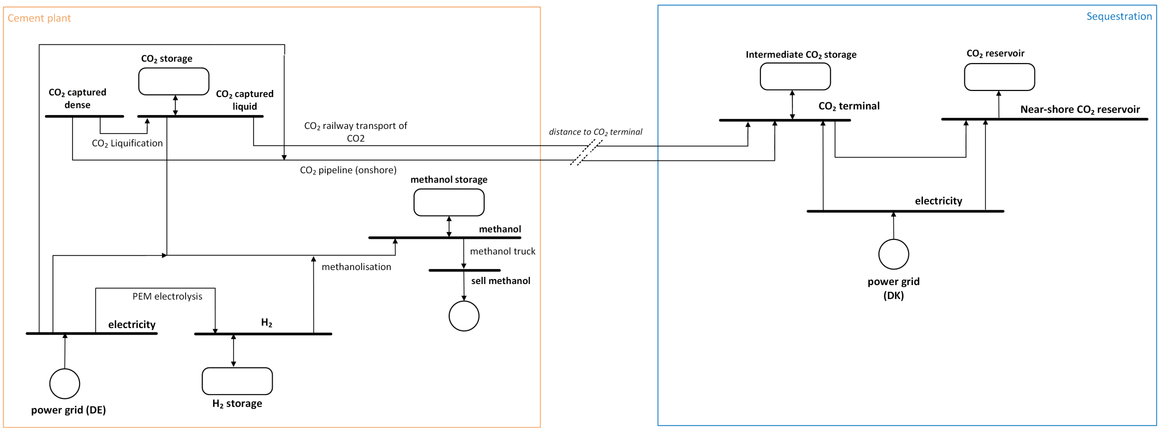

Figure 2: Implementation setup of the CO_2 post-processing either onsite via methanolisation or offsite via CO_2 transport and sequestration.

2.2. Energy System Optimization

The MILP model is optimized with respect to the total system costs C_{total}. Therefore, the objective function can be formulated as stated in Equation (1).

$$\text{minimise}\left(C_{\mathrm{total}} = \sum_{t} \sum_{C} \mathrm{CAPEX}_{\mathrm{annual},C,t} + \mathrm{OPEX}_{\mathrm{annual},t} \right) \tag{1}$$

Whereas $\mathrm{CAPEX}_{\mathrm{annual},C,t}$ represents the annualized investment costs for each component c and each investment period t and $\text{OPEX}_{\text{annual},t}$ represents the operating costs of all energy carriers for each investment period t. The annualized investment costs are calculated using the annuity method according to Equation (2) and the calculation of the annual operating costs can be derived from Equation (3).

$$\text{CAPEX}_{\text{annual},C} = \text{CAPEX}_C \cdot \frac{(1+i)^n \cdot i}{(1+i)^n - 1} + \text{FOM}_C \tag{2}$$

Hereby, i represents the discount rate, and n is the payback period. CAPEX_C represents the total investment costs of the component given in $€/\text{MW}$ and FOM_C takes into account the fixed operation and maintenance costs. In the base case, i is set to $7\,\%$. The payback period n is always equivalent to the component's lifetime. The annual operational costs ($\text{OPEX}_{\text{annual}}$) are calculated as follows:

$$\text{OPEX}_{\text{annual}} = \sum_{e}^{E} \text{c}_e \cdot \bar{p}_{e,\text{ annual}} + \sum_{c}^{C} \text{VOM}_c \cdot \bar{p}_{c,\text{ annual}} + \bar{p}_{\text{CO}_2\text{ emitted}} \cdot \text{c}_{CO_2} - c_{\text{MeOH}} \cdot \bar{p}_{\text{MeOH, annual}} \tag{3}$$

In this context, c_e represents the costs of an energy carrier e in $€/\text{MWh}$, while $\bar{p}_{e,\text{ annual}}$ describes the annual dispatch in MW h. Additionally, the variable operation and maintenance costs VOM_c for each component's annual dispatch $\bar{p}_{c,\text{annual}}$ must be taken into account. $\bar{p}_{\text{CO}_2\text{ emitted}}$ represents the total annual CO_2 emissions, that have to be compensated within the CO_2 atmosphere balance and c_{CO_2} refers to the annual CO_2 price. $\bar{p}_{\text{MeOH, annual}}$ considers the annual produced methanol, with c_{MeOH} as methanol revenue. For all scenarios, the methanol revenue is oriented at today's market for fossil methanol and is set to $81\,€/\text{MWh}$.

Data sources

Table 1 summarizes the most relevant data sources from which the techno-economic assumptions of this study were derived. All costs are given in $€_{2020}$. An electricity price time series for Germany and Denmark (for sequestration) was obtained from the PyPSA-DE model. Hereby, the results were extracted from investment period 2045, assuming CO_2 neutrality in Germany. Since the PyPSA-DE model was optimized with $3\,\text{h}$ resolution, the time series is extended to $1\,\text{h}$ resolution manually by assigning the same electricity price three times.

Table 1: List of references for techno-economic assumptions of this study.

Category	Components	Source
Kiln oven systems	Retrofitting costs for fuel switching	[17, 14]
Feedstock prices	Gas, coal, alternative fuels	[18]
Electricity prices	Hourly electricity costs for DE and DK	[19]
Energy storage	H_2 and electrical storage	[16]
Carbon Capture	Amine and oxyfuel-based capturing	[20]
CO_2 Transport	Pipeline and pumping station	[20]
CO_2 Transport	Railway and buffer storage	[21]
CO_2 Sequestration	CO_2 terminal and sequestration	[20]
MeOH Synthesis	H_2 electrolyzer, MeOH plant, storage	[22]

Key Modeling Constraints

In order to adequately model investment decisions and the operating behaviour of crucial technology, this study incorporates an MILP modeling approach. To allow for reproducibility, in the following section, the most important constraints are briefly summarized.

As previously mentioned, there is no demand attached to the methanol balance. Instead, methanol can be sold once a day, whereas the amount of exported methanol may vary during the year. Equation 4 takes this into account.

$$\bar{p}_t^{\text{MeOH}} = \bar{D}^{\text{MeOH}}_{\text{day, max}} \cdot \bar{b}_{d(t)} \qquad \forall t \in \mathcal{T}_{\text{pickup}} \tag{4}$$

With $\bar{p}_t^{\text{MeOH}}$ as daily exported methanol and $\bar{D}^{\text{MeOH}}_{\text{day, max}}$ as the maximum daily sold methanol over the year. $\bar{b}_{d(t)}$ denotes the binary variable for deciding whether the amount of methanol according to $\bar{D}^{\text{MeOH}}_{\text{day, max}}$ should be sold or not. $\mathcal{T}_{\text{pickup}}$ is the daily pickup time, which is set to 10 a.m. for all scenarios. A minimum partial load constraint is added for the methanolisation plant following the approach of [23] by defining $\tilde{M}$ as a sufficiently high number (see equation 5). For other components, such as capturing technologies and oven systems, maximum ramps are used instead to curtail the model's computational costs.

$$\alpha_{\text{MeOH}} \cdot \bar{P}_{\text{nom, MeOH}} \leq \bar{p}_{\text{t, MeOH}} + \tilde{M} \cdot \left(1 - \bar{b}_{t,\text{MeOH}}\right) \qquad \forall t \in \mathcal{T} \tag{5a}$$

$$\bar{p}_{\text{t, MeOH}} \leq \tilde{M}\bar{b}_{t,\text{MeOH}} \qquad \forall t \in \mathcal{T} \tag{5b}$$

With the minimum partial load α_M assumed to $10\,\%$ [24]. Furthermore, $\bar{p}_{\text{t, MeOH}}$ represents the hourly dispatch of the methanol plant and $\bar{P}_{\text{nom, MeOH}}$ is the optimized capacity.

Lastly, minimum extendable capacities are defined for CAPEX-intensive investments to take into account effects due to economy of scale. These components incorporate amine-based and oxyfuel-based CO_2 capturing plants, dense CO_2 pipeline, the CO_2 terminal and the near-shore sequestration reservoir. Thresholds for each component were based either on existing projects or literature [25, 16, 22, 26] and implemented as depicted in Equation 6. Again, $\tilde{M}$ represents a sufficiently high number.

$$P_{\text{nom, c, min}} \leq \bar{P}_{\text{nom, c}} \cdot \bar{b}_c \qquad \forall c \tag{6a}$$

$$\bar{P}_{\text{nom, c}} \leq \tilde{M} \cdot \bar{b}_c \qquad \forall c \tag{6b}$$

With $P_{\text{nom, c, min}}$ as minimum extendable capacity threshold, $\bar{P}_{\text{nom, c}}$ as decision variable for the component's capacity, and $\bar{b}_c$ as binary decision variable.

To ensure that only either an oxyfuel-based or an amine-based system may be built, one additional constraint (see Equation 7) must be added, forcing the sum of both corresponding binaries must not exceed one.

$$\bar{b}_{\text{Amine}} + \bar{b}_{\text{Oxyfuel}} \leq 1 \tag{7}$$

Calculation of Levelized Costs of CCS and CCU

In this study, the levelized costs are calculated for CO_2 capture, transport, and storage (LCO_{CTS}) and for CO_2 capture and conversion to methanol (LCO_{CCU}) to compare both pathways. LOC_{CTS} include capturing, conditioning, transport, and storage and are calculated according to Equation 8. LOC_{CCU} encompasses capturing, conditioning, and methanolisation, and are calculated according to Equation 9. When enabling both pathways, capturing technologies contributing to the levelized costs, i.e. amine-based and oxyfuel capturing plants and CO_2 buffer storage tank, need to be allocated either to LCO_{CTS} or LCT_{CCU} according to how the annual captured CO_2 is processed.

$$LCO_{\text{CTS}} = \frac{C^{\text{cap}}_{\text{CTS}} + C^{\text{var}}_{\text{CTS}}}{\sum \dot{m}_{\text{CO}_2,\text{storage}}(t)} \tag{8}$$

$$LCO_{\text{CCU}} = \frac{C^{\text{cap}}_{\text{CCU}} + C^{\text{var}}_{\text{CTU}}}{\sum \dot{m}_{\text{CO}_2,\text{MeOH}}(t)} \tag{9}$$

With $C^{\text{cap}}_{\text{CTS/CCU}}$ as capital expenditures allocated to CO_2 capture, transport, and storage or CO_2 capture and conversion to methanol, whereas $C^{\text{var}}_{\text{CTS/CCU}}$ represents the variable costs accordingly. Variable costs also include electricity costs. Finally, $\sum \dot{m}_{\text{CO}_2,\text{storage/MeOH}}(t)$ accounts for the annual amount of CO_2 either being sequestrated or converted to methanol.

2.3. Introduction of Case Studies

In the following section, the case studies are briefly summarized. If not indicated, techno-economic assumptions and exogenous modeling parameters, such as the pick-up hour for methanol exports, railway departure, cement plant distance to the CO_2 terminal, or the electricity import and CO_2 prices, are identical for all cases.

Carbon Capture and Sequestration (CCS)

In the first case study, only sequestration is allowed for handling the captured CO_2. A model constraint requiring annual CO_2 neutrality is implemented to ensure that CO_2 must be captured and sequestered. Again, it should be noted that net CO_2 neutrality is possible due to the biogenic carbon share of the alternative fuels. The CO_2 price is assumed constant as introduced in section 2.. LCO_{CTS} are calculated for a varying distance (100 to $2000\,\text{km}$) between the cement plant and the CO_2 sequestration terminal. Furthermore, the influence on transport via railway vs. pipeline will be investigated.

Carbon Capture and Sequestration or Conversion to Methanol (CCUS)

In the second study, both CO_2 conversion pathways are modeled. Hereby, no constraint enforcing net CO_2 neutrality is applied. Instead, the impact of the CO_2 price is examined. For each distance, the CO_2 price is assessed between 100 and $300\,€/\text{t}_{\text{CO}_2}$ with an increment of $50\,€/\text{t}_{\text{CO}_2}$. The distances range from 200 to $2000\,\text{km}$, with increments of $250\,\text{km}$.

3. Results

In the following section, the results of the previously introduced scenarios are presented.

3.1. Carbon Capture and Sequestration Benchmark Scenario

The results of the levelized costs of CO_2 capture, transport, and sequestration for varying distances between the cement plant and the sequestration site are visualized as a stacked bar in Figure 3. Hereby, the LCO_{CTS} are split into their main contributors. Furthermore, the transport share of the pipeline and the railway based on the total transported CO_2 and the net CO_2 emissions is indicated as well. Negative CO_2 emissions are possible due to the biogenic share of the alternative fuels and may be economic due to the CO_2 price set as $210\,€/\text{t}_{\text{CO}_2}$.
As visualized in Figure 3, the distance heavily influences the LCO_{CTS}. The net CO_2 emissions are lowest for distances below $300\,\text{km}$. At short distances, CO_2 transport relies on both rail and pipeline transport. Here, the train's capacity is expanded first before additional pipeline capacity is required. Overall, the investment costs of the pipeline dominate the levelized costs. The transport capacity via railway is indirectly curtailed to avoid the need for expanding the CO_2 storage capacity of the terminal (MILP decision). The maximum injection capacity of $500\,\text{t}_{\text{CO}_2}/\text{h}$ therefore predefines the threshold for CO_2 transport via railway without requiring the expansion of the minimum CO_2 terminal storage. Since railway transport uses liquefied CO_2 and pipeline transport only dense CO_2, the expanded capacities of capture technologies correlate with the preferred transport option. When Pipeline transport dominates, the chosen capturing technology is the amine-based component. Whereas, when the pipeline share decreases, the system switches to oxyfuel. Even though parallel operation of oxyfuel-based and amine-based capturing is excluded by the constraint presented in Equation 7, liquification of captured CO_2 from the amine-based process is allowed. In Figure 3, the corresponding investment costs are associated with the oxyfuel component. Therefore, for distances up to $500\,\text{km}$ oxyfuel and

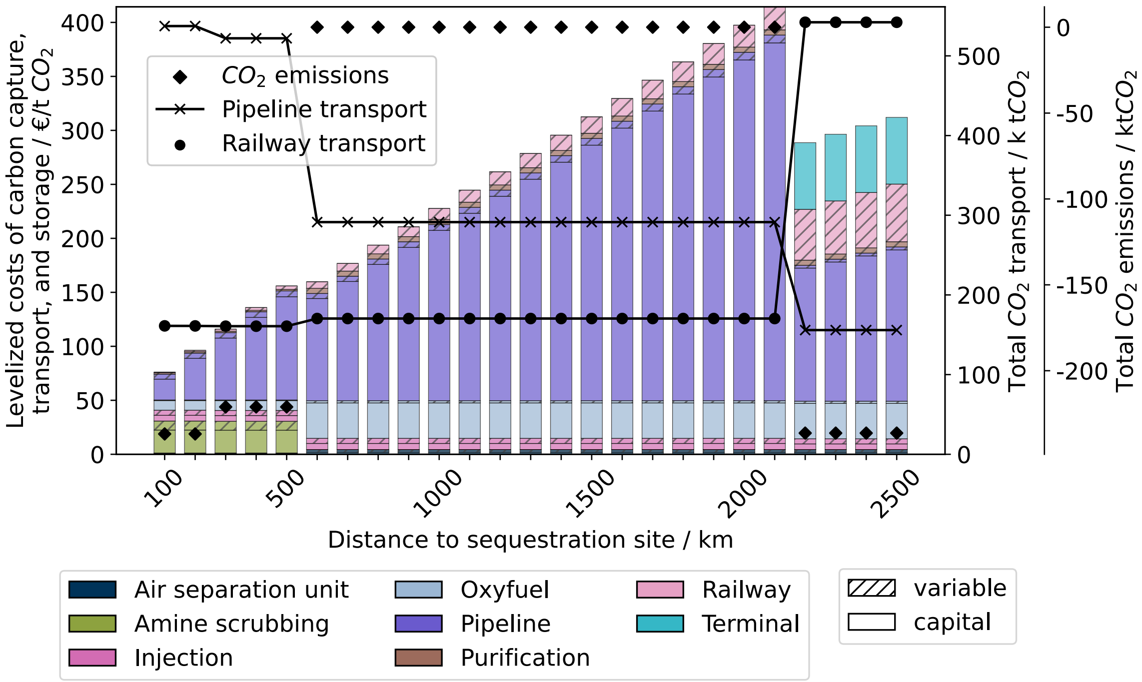

Figure 3: Levelized Costs of Capturing, Transport, and Storage for varying distance between the cement plant and the sequestration site. Additionally, CO_2 transport capacities via pipeline or railway and net CO_2 emissions are shown.

amine scrubbing both contribute to the LCO_{CCS}.

For distances exceeding $300\,\mathrm{km}$, the total CO_2 emissions are increased significantly and CO_2 neutrality is only achieved due to the constraint. Furthermore, the ratio between pipeline and railway transport is more or less constant, whereas the capital cost of the pipeline dominates the LCO_{CTS}. The preferred capturing technology switches to oxyfuel-based capturing. Another switching point can be observed at a distance of $2100\,\mathrm{km}$. Here, the transport capacity of the pipeline decreases significantly. In contrast, the train-based CO_2 transport now exceeds the threshold of the injection pipeline capacity, enforcing the expansion of the CO_2 terminal. Since the investment costs of the pipeline directly scale with the distance to the sequestration site, expanding the CO_2 terminal allows increasing the train's transport capacity and thus, decreasing the required capacity of the CO_2 pipeline. The exploitation of the terminal buffer storage even leads to net-negative CO_2 emissions. The LCO_{CTS} decreases since the quantity of captured CO_2 increases. In general, it should be critically reflected that within Europe, distances to the closest sequestration site are only rarely exceeding $1500\,\mathrm{km}$.

3.2. Carbon Capture and Sequestration or Conversion to Methanol

The results of the CCUS case study are presented in Figure 4 as bar charts. In addition to total CO_2 emissions, the transport type for CCS and the share of CO_2 converted to methanol are visualized. Captured CO_2 to either CCS or CCU corresponds to the total amount sequestrated or sold as methanol. From the results, it can be derived that for low distances to a sequestration site, CCS is preferred over CCU. Hereby, the CO_2 price affects the quantities of sequestrated CO_2. Again, CO_2 transport via pipeline is preferred for short distances, whereas for longer distances, the railway transport share is dominating. For distances between 500 and $1000\,\mathrm{km}$ and high CO_2 prices exceeding $200\,€/\mathrm{t}_{CO_2}$, CO_2 sequestration via railway dominates. In general, CO_2 prices exceeding $200\,€/\mathrm{t}_{CO_2}$ are enabling net-negative CO_2 emissions, regardless of the transport distance. For the lowest transport distance, even CO_2 prices of $100\,€/\mathrm{t}_{CO_2}$ already enable sequestration. However, the amount is curtailed by the daily train capacity. Therefore, no CO_2 neutrality is achieved. CO_2 conversion to methanol does only seem to be competitive for high distances and high CO_2 prices. Furthermore, CCU is not completely replacing sequestration. Instead, the expansion of CCU enables maintaining the maximum threshold

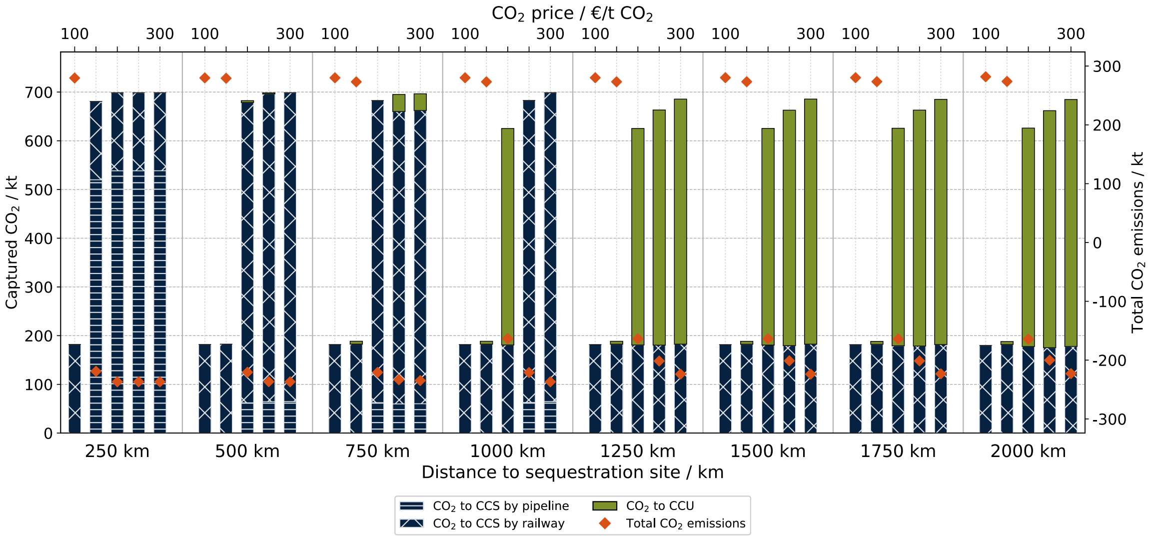

Figure 4: Sequestration and Utilization for varying CO_2 price and distance between the cement plant and the sequestration site.

for railway-based CO_2 transport without requiring CO_2 terminal expansion. Once this switching point is reached, the CCS-to-CCU share seems to depend solely on the CO_2 price and thus affects the total CO_2 emissions. In addition, the total amount of captured CO_2 decreases with the introduction of methanolisation. Since the H_2 required for the methanol synthesis can only be produced onsite, not all CO_2 is converted to counter periods of high electricity prices. The total amount of captured CO_2 is therefore marginally affected by the CO_2 price. For medium sequestration distances and high CO_2 prices, methanolisation and sequestration seem to be almost balanced as indicated by switching CCU capacities.

4. Discussion

Only a few comparable studies quantifying the levelized cost of CCS have been published in the literature. Most studies on industrial carbon capture and storage cost use CO_2 avoidance cost, thus having a different calculation reference [27, 28, 29]. One of the studies that aligns with the specific costs of capture, transport, and storage per tonne was published by Johnsson, Normann, and Svensson [30]. Here, the authors aggregated the costs required to sequester the emissions of 28 Swedish industrial plants, each emitting at least $500\,\mathrm{kt}$ CO_2 per year. Their results range between 83 and $140\,€_{2020}/\mathrm{t}_{CO_2}$, which is comparable to the LCO_{CTS} presented in this study. Mendelevitch et al. [31] assessed the cost of transport and storage, regarding different transport options. Although their scope of research didn't include the cost of Carbon capture, they concluded total cost of capturing, transport and storing CO_2 to be within the range of was the range of 112 and $224\,€_{2020}/\mathrm{t}_{CO_2}$. The average Methanol price in the reference case of this study, when only allowing CCU and forcing CO_2 neutrality was found at about $121\,€/\mathrm{MWh}_{\mathrm{MeOH}}$, which amounts to $667.92\,€/\mathrm{t}_{\mathrm{MeOH}}$ using $5.52\,\mathrm{MWh}/\mathrm{t}_{\mathrm{MeOH}}$ [22]. Other studies that are comparable to the assumptions of this study, by including all CAPEX and OPEX costs of capture and conversion to methanol, and by using PEM electrolysis, provide higher costs. For instance, Meunier et al. [32] computed the cost of capturing and utilizing CO_2 from a cement plant to be $795\,\mathrm{MWh}/\mathrm{t}_{\mathrm{MeOH}}$. The limited CO_2 intake per day of 2.2 tonnes per day for 1.5 tonnes per day reduces its competitiveness, though. Bellotti, Daria et al. [33] and Sollai et al. [15] provide the values of $797\,€/\mathrm{t}_{\mathrm{MeOH}}$ and $876\,€/\mathrm{t}_{\mathrm{MeOH}}$ respectively, in the context of capture from a coal-fired power plant. As Bellotti, Daria et al. [33] provided a range of different costs depending on the operating pressure of the synthesis, the cost value was computed as the average between 50 and $100\,\mathrm{bar}$. It should be noted that neither this study nor the mentioned values from the studies include the revenues of selling methanol or oxygen, but only state the pure specific cost of the methanol production. Finally, in the scenario allowing CCS and CCU to be expanded simultaneously, it was demonstrated that methanolisation can only be competitive for high CO_2 prices and high transport distances. However, in this study, the revenue was based on today's market for fossil methanol. Since the model tends to choose a high share of biogenic fuels for deriving the process heat, the produced methanol has an approximate biogenic share of $35.763\,\%$. Therefore, future work should include a sensitivity study assessing the influence of the methanol revenue on the CCS vs. CCU decision.

5. Conclusion

In this study, a MILP bottom-up model of a cement plant was introduced and optimized for achieving CO_2 neutrality. It was demonstrated that the preferred CO_2 transport option depends heavily on the distance to the sequestration site and the CO_2. Furthermore, a strong correlation with the investment decision on capture technology was observed: Oxyfuel was found dominant when CO_2 is predominantly transported via railway, since the CO_2 is already in liquid form after the oxyfuel process, whereas the amine scrubber is more beneficial when CO_2 is predominantly transported via pipeline. When enforcing carbon capture and conversion to methanol, oxyfuel emerges as a preferred capture technology due to the beneficial O_2 coupling from the PEM electrolyzer. Enabling both CO_2 management options demonstrated that, within reasonable distances to the sequestration site, the model mainly focused on CCS. Even for low CO_2 prices of $100\,€/t_{CO_2}$, cement plants located close to potential sequestration sites could reduce their CO_2 emissions. For CO_2 prices exceeding $200\,€/t_{CO_2}$, the cement plant reached net-negative CO_2 emissions regardless of the distance to the sequestration site. Greater distances to the sequestration site enable a switch to methanolisation but result in lower total captured CO_2 emissions.

NOMENCLATURE

Abbreviations

CAPEX	Capital expenditure
CCS	Carbon capture and sequestration
CCU	Carbon capture and utilization
FLH	Full load hours
FOM	Fixed operating and maintenance cost
LCO	Levelized costs of x
MeOH	Methanol
MILP	Mixed-integer linear programming
OPEX	Operating expenditure
PEM	Proton exchange membrane electrolyzer
PyPSA	python for power system analysis
VOM	Variable operating and maintenance cost

Superscripts and Subscripts

annual	annualized costs
c	component
CCU	Carbon capture and utilization
CTS	Carbon capture, transport, and sequestration
e	energy carrier
el	electric
t	investment period
th	thermal

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Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly to improve language and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.