Decarbonization pathways of the Swiss cement industry towards net zero emissions

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A B S T R A C T

The present study investigates long-term energy consumption and CO2 emission pathways of the Swiss cement industry, including pathways towards net zero CO2 emissions by 2050. Cement production accounts for 8% (12.8 PJ) of the final energy consumption and 36% (2.5 Mt) of the CO2 emissions in the Swiss industrial sector in 2015. Using a techno-economic bottom-up optimization model based on the TIMES (The Integrated MARKAL-EFOM System) modeling framework, this study applies an advanced modeling technique for the Swiss TIMES Energy system Model (STEM) that expands the modeling of energy flows with additional material and product flow modeling. This allows a more detailed technology representation as well as to account for process related emissions in the cement sector. This modeling framework is applied for a scenario analysis focusing on energy efficiency as well as decarbonization, which ultimately contributes to an improved understanding of energy technology development and identifies policy strategies for the realization of a decarbonized cement industry. The results show that, in accordance with current trends, future cement production reduces its specific energy consumption from 3.0 GJ/tcement in 2015 to 2.3 GJ/tcement in 2050. Simultaneously, cement production decreases its CO2 emission intensity from 579 kgCO2/tcement in 2015 to 466 kgCO2/tcement in 2050 due to the decreasing average clinker content in cement and energy efficiency improvements. Even without major climate policy intervention in the future, it is economically beneficial to replace and improve the existing equipment with more energy efficient technologies. However, our results show that for a drastic reduction of the CO2 emissions in order to comply with the goals of the Paris Agreement, the cement sectors relies on CO2 capture because of the process related emissions. The results show that a minimum CO2 tax of 70 EUR/tCO2 is required for the CO2 capture technologies to become economically competitive.

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1. Introduction

1.1. Energy consumption and CO2 emissions in the Swiss industry

The Swiss industry sector accounts for 18% of the total final energy consumption in 2015 and 12% of the total carbon dioxide (CO2) emissions in Switzerland (Bundesamt für Energie BFE, 2016). The Swiss Energy Strategy 2050 (SES) that was accepted in 2017 by a public referendum features a per capita reduction in final energy consumption of 43% and an electricity reduction per capita of 13% until 2035 from 2000 levels (International Energy Agency IEA, 2018). Furthermore, Switzerland ratified the Paris Agreement in 2017 and therefore agreed to pursue efforts to limit the global temperature increase to 1.5 °C above pre-industrial levels. As one of the main energy demand sectors and as a CO2 intensive sector, the contribution of the industry towards these policy goals is to be assessed. Furthermore, reaching the energy and CO2 reduction goals should not affect the economic competitiveness of the Swiss industry, because this sector provides the second most jobs in Switzerland (only after the services sector) and employs approximately one million people (Federal Statistical Office FSO, 2019). From an economic perspective, the main barriers for energy efficiency in industry are financial risks with low returns on investments (i.e. long payback periods) whereas industries tend to seek high rate of returns. Therefore, it is vital to understand the Swiss industry sector’s energy technology options, its interdependencies and assess its developments. The present research focuses on long-term...
energy and emission pathways to assess the contribution of the cement sector towards an energy efficient and decarbonized Swiss industry.

1.2. Swiss cement industry

The Swiss cement industry accounts for 8.3% (Cemsuisse, 2018), (Bundesamt für Energie BFE, 2016) of the final energy consumption and 35.5% (Cemsuisse, 2018), (Federal Office for the Environment FOEN, 2018) of the CO₂ emissions in the Swiss industrial sector in 2015. The high share of CO₂ emissions results from process related emissions from clinker production - the main constituent of Portland cement. Six cement plants with a total cement production capacity of almost 5 Mt mainly cover the domestic cement demand in Switzerland (Table 1). Cement imports and exports are around 0.8 Mt and 0.15 Mt respectively, which results in a net import of 0.65 Mt. The demand for cement is expected to remain stable (International Energy Agency, 2018), even to decrease (Prognos, 2012), therefore no production capacity expansion or even to decrease (Prognos, 2012), therefore no production capacity expansion is expected in the foreseeable future. Nevertheless, continuous production from the existing plants is inevitable to avoid dependency on imported cements. This means that it is important to consider technology retrofit and upgrade options to improve the energy efficiency of the existing plants.

Swiss cement plants have an average specific final energy use of 3.0 GJ/tcement or 4.1 GJ/tclinker (Cemsuisse, 2018) (Fig. 1). Benchmarking the Swiss cement production to the global cement industry which consumes between 3.4 GJ/tclinker and 4.7 GJ/tclinker (Cement Sustainability Initiative (CSI), 2017a), the Swiss cement industry belongs to the most energy efficient production facilities in the world. This is partly due to the energy efficient dry process. Nonetheless, compared to the best available techniques (BAT) with an energy intensity of 3.3 GJ/tclinker (European Commission, 2013), there is still potential for energy efficiency improvement. The average specific CO₂ emissions of the Swiss cement plants are 787 kgCO₂/tclinker, which is lower than the EU average of 825 kgCO₂/tclinker or the world average of 843 kgCO₂/tclinker (Cement Sustainability Initiative (CSI, 2017a)). On one hand, this is a direct result from the low specific energy consumption and on the other hand, the Swiss cement plants burn a comparably high share of alternative fuels such as biomass and wastes. Two thirds of the CO₂ emissions from the cement industry are related to the process of converting limestone into clinker. During the last decades, these process related emissions decreased due to the reduction of clinker content in cements (see Fig. 2). Still they represent a major source of CO₂ emissions. For the analysis of emission mitigation options it is therefore fundamental to consider CO₂ emission mitigation options for the process related emissions additional to the energy related CO₂ emission mitigation options.

Table 1
Production capacity of the Swiss cement industry (based on (Zuberi and Patel, 2017), (Winskel, 2020), (Cemsuisse, 2018)).

| Location | Company | Process type | Clinker production [Mt/yr] | Cement production [Mt/yr] |
|----------|---------|--------------|---------------------------|--------------------------|
| Untervaz | Lafarge | Dry          | 0.60                      | 0.80                     |
| Eclépens | Holcim | Dry          | 0.70                      | 0.90                     |
| Siggenthal | Lafarge-Holcim | Dry | 0.75 | 1.00 |
| Wildegg | Jura Cement | Dry | 0.64 | 0.85 |
| Cornaux | Jura Cement | Semi Dry | 0.24 | 0.30 |
| Reuchenette | Vigier Cement | Dry | 0.80 | 1.02 |

# Imports and exports are exclusively with surrounding countries from the EU.
are still missing. On the other hand, holistic energy system analysis, for example with the Swiss TIMES energy system model (STEM) (Kannan and Turton, 2014) or the Swiss Energy Strategy 2050 (Prognos, 2012), contributed to the understanding of energy technology development and identified policy strategies to reach the climate goals. However, an in-depth understanding of the energy technologies, industrial production processes and the interdependencies of the industrial sector in a system context is lacking.

Furthermore, techno-economic models for the global cement industries have been used to analyze long-term development on a global scale, but they lack representation of national policy strategies and have very limited country-specific technological details (Ruijven et al., 2016), (Kesicki and Yanagisawa, 2015), (Kuder, 2014). Besides the global models, there are also national or regional model-based studies (Ke et al., 2012), (Dutta and Mukherjee, 2010). But the baseline for the Swiss cement industry is not captured by these studies and therefore, the insights cannot be directly transferred. Studies focusing on potentials in the cement industry within the EU are often very technology-rich but miss the system implications and focus on potentials while neglecting pathways to reach them (Brunke and Blesl, 2014), (Blesl and Kessler, 2013), (Moya et al., 2011). In addition to this, many techno-economic models focus on the traditional cement making process or the application of CO₂ capture and storage (CCS) (Jakobsen et al., 2017), (Voldsund et al., 2019), (Gardarsdottir et al., 2019), but do not include new production paths (e.g. recycling paths, alternative binders, alternative supplementary cementitious materials (SCM)). In order to overcome these research gaps, the overarching goal of the methodology in this study (described in section 2) is to expand the benefits of a techno-economic energy system model (STEM) with a more detailed technological representation including production processes and material flows.

The paper is organized as follows: The modeling of cement production processes in the TIMES framework is described in section 2 along with technological assumption and scenario definitions. The results of the scenario analysis are presented in section 3 followed by a discussion in section 4 and a conclusion in section 5.

2. Methodology

An integrated techno-economic modeling framework is developed and applied for scenario analysis until 2050. The analysis of the industry sector is performed using STEM, developed at Paul Scherrer Institute (PSI). STEM was developed using The Integrated MARKAL-EFOM System (TIMES) modeling framework developed in the International Energy Agency (IEA)’s Energy Technology System Analysis Program (ETSAP) (Loulou et al., 2016). STEM contributes to the understanding of energy technology development and identifies policy strategies for the realization of a sustainable Swiss energy system. Within this framework, the industry sector in STEM is improved with a more detailed representation at a sub-sectoral level including the most energy-intense branches. One fundamental methodological advancement is moving from modeling energy flows only to modeling of products and processes with energy and material flows. To our knowledge, this is the first time that energy and material flows are combined in a TIMES modeling framework with a very high technology representation of specific industrial sectors at a national scale. This scope extension allows to account for efficiency improvements of specific technology developments or process modifications. Taking into consideration that the cement sector has significant process related CO₂ emissions, this approach is more relevant to explore mitigation options.

The previous work with STEM (Kannan and Turton, 2014), (Kannan, 2018), (Panos et al., 2019) does include process related emissions, but applies emission coefficients to track the process related emission whereas the work presented in this paper includes explicit modeling of the cement production process, which is described in the following section.
2.1. Modeling of process steps with material flows

As highlighted earlier, the conventional energy-flow-based modeling approach used in the TIMES framework is expanded with material and product flows in addition to energy flows. This combination allows for a more accurate analysis with the advantage of analyzing individual process step improvements (with both material and energy substitutions) and to account for process related CO2 emissions. Furthermore, the new approach supports to investigate implications of technological change on material and production prices (or costs) which can be extracted as a direct result from the model (e.g. CO2 abatement costs and its impact on cement production cost etc.).

Fig. 3 shows the extended modeling approach of the material and energy flows in a simplified schematic overview. The process diagram of the entire cement process is presented in Fig. 4. The model is very technology-rich including for example technologies like multiple calcinations and kiln technologies, as well as CO2 capture methods and carbonation of waste concrete. The left-hand side in Fig. 4 represents the production process to produce cement. Almost 90% of the energy required to produce cement is thermal energy, of which 65% is consumed in the precalciner and 35% in the kiln. Energy related CO2 emissions from fuel combustion and process related emissions from chemical conversion are implemented in the model in connection with the kiln and precalciner. Furthermore, options to recover waste-heat that can be reused on site or in the model in connection with the kiln and precalciner. Further-

The modeling of the production process also includes options to capture and store or reuse both energy and process-related CO2 emissions. The right-hand side in Fig. 4 shows the processes related to material recovery from demolished concrete. The demolished concrete can either be used as aggregates in concrete manufacturing, as supplementary cementitious material (SCM) in the cement plant or it can be carbonated with captured CO2 to reuse the resulting calcium carbonate as raw material in the cement process or to sell it on the market.

For most of the process steps shown in Fig. 4 different technological options are available to the model. The overview of technologies is provided in the appendix A1. The options for kilns and precalciners are presented in Table 2 with their specific electricity and heat consumptions. Where relevant, technology options are available as retrofit of the existing processes to improve the energy efficiency. For example, the upgraded kiln with cyclone preheater and precalciner and the upgraded kiln with low pressure drop cyclone are options to retrofit the kiln with cyclone preheater and precalciner or they can be built as a new installation.

The existing kilns in the six cement production facilities in Switzerland are included as technology stock in the base year 2015 and their remaining lifetime is included based on an estimated decommissioning curve. The start of the decommissioning curve for each kiln technology depends on its up-to-dateness. The estimated decommissioning of the existing kiln capacity is shown in Fig. 5. However, this is an approximation as in reality the kilns would decommission step-wise. The model also considers the possibility to retire the existing capacity before reaching the end of its lifetime. The retired capacity is replaced with new investments in kilns in order to fulfill the exogenously given cement demand. This decommissioning approach is not only applied to the existing kilns, but also to all the other equipment in the cement plant.

2.2. Data sources

An overview of the technology data used in this model is shown in the appendix A2. The database includes technological parameters (e.g. efficiency, lifetime) and economical parameters (e.g. investment costs, operational and maintenance costs). The data is mainly collected from the cement sustainability initiative (Cement Sustainability Initiative CSI, 2017b), the best available technique (BAT) reference document from the European Commission (European Commission, 2013) and various research papers (Zuberi and Patel, 2017), (Voldsund et al., 2019), (Gardarsdottir et al., 2019), (Volkart et al., 2013), (Pasquier et al., 2018), (Madlool et al., 2011), (Katsuyma et al., 2005) and reports (United States Environmental Protection Agency, 2013), (Hoppe et al., 2018), (Institute for Industrial Productivity, 2014), (WSP and Parsons Brinckerhoff, 2015), (International Energy Agency IEA, 2013). In addition to currency conversion, technology costs from outside Switzerland are adjusted to Swiss conditions with the following methodology based on (Zuberi and Patel, 2017) to account for the higher labor
costs which typically exist in Switzerland compared to other countries.

\[ \text{TC}_{y, CH} = (S_{EC,y} \cdot CF_{EC} + S_{LC,y} \cdot CF_{LC,z}) \cdot TC_{y,z} \]

where: \( \text{TC}_{y, CH} \) = Total cost for technology \( y \) in Switzerland.

\( \text{TC}_{y,z} \) = Total cost for technology \( y \) in region \( z \)

\( S_{EC,y} \) = Share of equipment cost on total costs of technology \( y \)

\( S_{LC,y} \) = Share of labor costs on total costs of technology \( y \)

\( CF_{LC,z} \) = Cost factor for labor costs from region \( z \) to Switzerland (appendix A3)

\( CF_{EC} \) = Cost factor for equipment costs (= 1)

2.3. General assumptions and scenario definition

The overall objective function of the model is to meet an exogenously defined cement demands at least cost by accounting for energy and material related costs. We analyze four broad scenario groups focusing on energy efficiency and CO\(_2\) emission reduction. For all the scenarios, the following common set of assumptions is made, which is followed by scenario specific assumptions and boundary conditions:

- The domestic production of cement is assumed to remain stable (International Energy Agency, 2018).

| Kiln type                                      | Spec. electricity consumption [GJ/t clinker] | Spec. heat consumption [GJ/t clinker] |
|------------------------------------------------|---------------------------------------------|---------------------------------------|
| Lepol kiln                                     | 0.16                                        | 3.02                                  |
| Kiln with cyclone preheater and precalciner    | 0.14                                        | 2.44                                  |
| Upgraded kiln with cyclone preheater and precalciner | 0.14                                      | 2.16                                  |
| Upgraded kiln with low pressure drop cyclone   | 0.13                                        | 2.16                                  |

Fig. 4. Modeling of the cement process with material recycling paths including all major material and energy flows.
- A social discount rate of 2.5% is defined and a technology specific discount rate\(^6\) of 8% (based on (Zuberi and Patel, 2017) and (Gardarsdottir et al., 2019)) for new process technologies is defined to account for risk and uncertainty associated with new technologies.
- The average clinker content in cement is assumed to decrease from 73.6% in 2015 to 60% in 2050 reflecting the impact of alternative cement chemistry, more efficient binders and improvements on SCM. For certain cement mixtures the technical limit goes even down to a share of 40% of clinker (Scrivener, 2019).
- A maximum share of 50% of coal in the fuel mix is defined as an upper boundary condition. In 2015 the share of coal in the fuel mix was at 43% (CemSuisse, 2018). Furthermore, the maximum net consumption of industrial waste is constant at 2015 levels. However, it is assumed that the consumption of bio-waste can be increased if it is economical.
- \(\text{CO}_2\) capture and storage (CCS) is available from 2030 onwards to capture \(\text{CO}_2\) from energy use and conversion processes. Currently, multiple test facilities are planed globally to investigate the application of CCS in cement plants (Pro Global Media, n.d.).

For the scenario analysis, the following four scenario groups with parametric variation within each group were defined:

- **BAU - Business as usual**

  In the business as usual scenario, the market environment and the policy framework are assumed unchanged. A \(\text{CO}_2\) tax of 20 EUR/t\(\text{CO}_2\) is applied over the entire period from 2015 to 2050.\(^7\)

- **CAP - \(\text{CO}_2\) Cap scenario group**

  In addition to the assumptions from the BAU scenario, a linear reduction of the \(\text{CO}_2\) emissions by 2050 compared to 2015 levels is applied as a cap. The reduction targets are defined in 2050 at 40%, 60%, 80% and 100%. For the \(\text{CO}_2\) captured, a downstream cost for utilization or sequestration of 20 EUR/t\(\text{CO}_2\) is assumed (based on (Intergovernmental Panel on Climate Change (IPCC, 2005))). The cap scenario group is analyzed with the assumption that CCS is available from 2030 as well as with an alternative assumption in which CCS will not be available due to technical or political limitations. These scenarios are indicated with “No CSS”. In the result section, the cap scenarios are denoted with suffix, e.g. CAP-60 refers to the 60% emission reduction target.

- **EE - Energy efficiency scenario group**

  The energy efficiency scenarios target a reduction of the specific energy consumption per ton of cement of 30% and 34% in 2050 compared to 2015 levels. All other assumptions from the BAU scenario are also implemented in this scenario group.

- **TAX - \(\text{CO}_2\) tax scenario group**

  This scenario group analyzes different tax policies compared to the BAU. Taxes are applied with a linear increase from 20 EUR/t\(\text{CO}_2\) in 2015 to a target value of 60–100 EUR/t\(\text{CO}_2\) in 2050. The tax scenarios are denoted with suffix, e.g. TAX-80 refers to a \(\text{CO}_2\) tax of 80 EUR/t\(\text{CO}_2\) in 2050 in the results section.

2.4. Limitations and scope

This study focusses on the cement industry with a special spotlight on production and process technologies. For a more holistic view on cement usage, the scope needs to be expanded to further include the whole value chain (Favier et al., 2018). With this approach, it would be possible to account for a more efficient usage of cement. Furthermore, novel cements (eg. Low energy CSA-belite cement, magnesium oxide cements (Favier et al., 2018)) and alternative clinkers (eg. Electrochemical clinkers (Cement Sustainability Initiative (CSI), 2017b), (Ellis et al., 2019), (UN Environment et al., 2018)) are not considered in this study, as they are not expected to meet more than 5% in 2030 and 10% in 2050 of the total cement demand and they are also not carbon free (Cembureau, 2013). Moreover, a detailed techno-economic analysis of the alternative fuels would exceed the scope of this study. Additionally, all implications of artificial intelligence (AI) on the cement industry were neglected. AI is expected to decrease the operational costs of the cement production and therefore decrease the cement price. As mentioned previously, no new capacity is expected to be added to the cement sector. Therefore, all process improvements are applied as retrofit options to the plant. However, in this model no economic punishment for the downtime of the plant is considered. In addition, the scope of the model includes clinker and cement production but neglects \(\text{CO}_2\) emissions assigned to the mining of supplementary material and all downstream processes (transport, distribution etc.). Especially the use of cement can be more efficient by improving structural elements or replacing cement by alternative building materials. In addition to this, it is assumed that the raw material reserves (mainly limestone) are sufficient for the domestic cement production. This is a valid assumption when

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\(^6\) The technology specific discount rate is used to calculate the annual payments resulting from a lump-sum investment in some year.

\(^7\) Since 2020, Switzerland is integrated to the EU ETS.
looking at the technical potential. However, there is a public resistance to expand the existing mining sites.

3. Results

The results from the scenario analysis are shown in this section, starting with an analysis of the energy consumption and the CO₂ emissions (chapter 3.1), followed by an analysis of the technologies, in particular kiln and CCS technologies (section 3.2), and a material flow analysis (section 3.3).

From the results of the business as usual scenario (explained in section 3.1), the target values of the scenario groups were increased incrementally (Fig. 6). This allowed to investigate the model dynamics, the model sensitivity and the limits for the boundary conditions. As a sensitivity analysis, the CAP scenarios are also analyzed under the assumption that CCS will not be available. This can only be done up to a 40% reduction of the CO₂ emissions, because of the process related emissions that cannot be avoided without CCS.

3.1. Energy consumption and CO₂ emissions

Fig. 7 shows the final energy consumption and the annual gross CO₂ emissions of the cement sector as defined in (Cement Sustainability Initiative (CSI, 2011)) of selected scenario results. In the business as usual scenario, a decrease of the final energy consumption by −24% from 2015 until 2050 can be observed. This is mainly due to the decreasing clinker content in cement and the replacement of existing process technologies at the end of their lifetime with more efficient technologies. This leads to a decrease in the specific energy consumption from 4.1 GJ/tclinker in 2015 to 3.8 GJ/tclinker in 2050. In absolute energy savings, highest gains are achieved with more efficient kilns and precalciners (−0.27 GJ/tclinker or −7%). Further improvements to reach the BAT value of 3.3 GJ/tclinker (European Commission, 2013) could be achieved with low pressure drop cyclones and with fuel switching. Under the process steps considered in this study, relatively high improvements in the specific energy consumption can be observed for cement milling. The electricity consumption of the cement mill decreases from 38.8 kWh/tcement in 2015 to 30.3 kWh/tcement (−22%) in 2050 due to the replacement of ball mills with vertical roller mills and the deployment of high efficiency classifiers for finishing grinding. However, the relative share of coal in the fuel mix slightly increases due to its low costs when CO₂ taxes are low, even though coal consumption still decreases in absolute terms. This is the case in the BAU scenario, in which we assume no restrictions concerning the CO₂ emissions. Nevertheless, because of the reduced energy consumption, the CO₂ emissions related to fuel combustion decrease accordingly (−21% from 2015 to 2050). In addition, the process related emissions decline proportionally to the clinker content in cement (−19% from 2015 to 2050) which leads to an overall reduction of the CO₂ emissions of 19% from 2015 to 2050.

The CO₂ tax scenarios indicate that there is no significant reduction of the CO₂ emissions compared to the BAU scenario with a tax up to 60 EUR/tCO₂. Only small shifts in fuel consumption from coal to bio-waste result in a minor reduction of the CO₂ emissions in 2050 (Fig. 8). But the CO₂ tax increases cement production cost, as cement plants have to pay for their emissions. Only a CO₂ tax higher than 60 EUR/tCO₂ makes CCS economically attractive which results in a drastic reduction of CO₂ emissions. This finding is broadly in line with other studies, such as (Ruijven et al., 2016) which reports a slightly higher value of 100 $/tCO₂ (50 EUR/tCO₂) for deep decarbonization of the cement sector through CCS. Even though CCS technology reduces emissions substantially, it increases the energy consumption. Depending on the CCS technology, heat is required for regeneration (MEA scrubbing and chilled ammonia process) or electricity is required for air separation (oxyfuel combustion). Because of the high share of oxyfuel combustion in the technology mix (see section 3.2.2), electricity consumption increases in particular. Nevertheless, part of the heat for MEA scrubbing and the chilled ammonia process can be recovered onsite from waste heat, which saves part of the costs for heat generation.

The comparison of the CO₂ emissions in the different scenarios in Fig. 8 shows that the annual CO₂ emissions remain the same in the energy efficiency scenarios or the CO₂ tax scenarios compared to the BAU until 2035, which means that no additional measures are employed. This indicates, that replacing old equipment with more energy efficient infrastructure can have economic advantages even without specific incentives to increase the energy efficiency or to lower CO₂ emissions.

When analyzing the scenario with 40% CO₂ reduction from 2015 until 2050 without CCS, the results show that the use of bio-waste as the main fuel is required in the long run (2050). It can be discussed whether this amount of bio-waste can be assigned to the cement sector. However, any further mitigation of the CO₂ emissions is not possible with fuel switching only, because the rest of the emissions are all related to the process of converting limestone into clinker. Avoiding these emissions would require CCS technology. Looking at CO₂ abatement costs in 2050 in Fig. 9, it can be observed that the CO₂ abatement costs are significantly higher and the potential for CO₂ mitigation is only around 40% when CCS is not available. The higher CO₂ abatement costs are then directly reflected in the cement production costs which almost double if CCS is unavailable.

A further decrease in energy intensity to a 30% reduction of the energy consumption per ton of cement in 2050 compared to 2015 can be reached by switching to low-carbon fuels like natural gas. However, fuel switching has only a marginal impact on the total CO₂ emissions.

The scenario analysis shows, that waste heat recovery and usage is highly dependent on assumed policies in place. In scenarios where CCS is deployed in the cement sector, the waste heat from the cement production process is re-used on site. In those scenarios, it is not economic to feed waste heat from the cement plant
Fig. 7. Final energy consumption and annual CO\textsubscript{2} emissions in the different scenarios.

Fig. 8. Scenario comparison of annual CO\textsubscript{2} emissions.
into a district heating network. Conversely, in scenarios where CCS is not deployed, waste heat remains available for alternative uses, such as distributed heat in the district heating networks. A full exploitation of the cement plants’ waste heat for delivery via district heating systems would imply an expansion of the corresponding heat supply infrastructure.

### 3.2. Technology review

#### 3.2.1. Kiln technologies

The existing kilns are decommissioned at the end of their lifetime as defined in the model (see section 2.1) and replaced by new upgraded kilns with cyclone preheaters and precalciners (Fig. 10). From the comparison of available technologies in the model and the technologies that are part of the cost-optimal solution, we conclude that some technologies, such as cyclones with low pressure drop, are not competitive. The savings in electricity do not pay off the higher investment cost, even if it could be retrofitted. These findings are in line with analyses of other studies such as (Zuberi and Patel, 2017). Even in the energy efficiency scenarios, the model results reveal to improve the energy efficiency rather by substituting fuels than by installing new cyclones with low pressure drops. However, a higher price for electricity may justifies the deployment of low pressure drop cyclone preheaters. However, this was not investigated further in this study.

Depending on the scenario, the existing lepol kiln, which is relatively energy inefficient compared the other kiln technologies, gets decommissioned well before the end of its lifetime. Due to the high fuel consumption compared to the other kilns, this kiln has relatively high operating costs. Because of the decreasing clinker content in cement, other plants can take over its production. A higher price for electricity may justifies the deployment of low pressure drop cyclone preheaters. However, this was not investigated further in this study.

The results show that under a least-cost configuration of the cement sector, parts of the existing kilns with cyclone preheater and precalciner are upgraded and retrofitted. Depending on the scenario, a higher or lower share of the existing kilns is retrofitted as it is not always economical to retrofit equipment that will soon reach the end of its lifetime. It should be noted that when talking of a new kiln, this is only one component of a cement plant. Therefore, this would correspond to a partial refurbishment of the a plant, but no new plants are built. However, replacing the kiln as the major component of a cement plant has high payback periods. Furthermore, the costs for the down-time of the cement plant when replacing an existing kiln is not considered.

To conclude the analysis of the kiln technologies the most important findings are:

- The total kiln capacity decreases due to the decreasing clinker content in cement.
- Upgrading and replacing the existing kilns with more efficient ones is recommended from an economical point of view in any of the scenarios.
- To reach a deep decarbonization of the cement sector, it is necessary to replace the some of the existing kilns, which are less energy efficient, with new energy efficient kilns even before reaching the end of their lifetime.
- Almost the same kiln technology is deployed across all scenarios which implies that the technology selection is robust.

#### 3.2.2. CCS technologies

Fig. 11 shows the installed CCS capacities of two the scenarios where CCS is deployed (TAX-80 and CAP-80) under the cost assumptions made in appendix A2.5. The first CCS technology available to the model in 2030 is MEA scrubbing. Because it is a post-combustion technology, existing kilns can be retrofitted without changing the fuel combustion unit and the production process. Therefore, MEA scrubbing is deployed if CO2 capture is needed in the near term. However, oxyfuel combustion is the most cost effective technology, but it is not a retrofit technology. The combustion is performed after removing nitrogen from the air, which changes the combustion kinetics. Therefore, only kilns that are newly built can be equipped with this technology. This means that MEA scrubbing and the chilled ammonia process are still needed in the deep decarbonization scenarios to retrofit the existing kilns. MEA scrubbing is the most cost effective technology if waste heat from the cement plant can be used for amine regeneration. If waste heat is unavailable, the chilled ammonia process is the preferred technology from an economical perspective. Changing prices for energy carrier could however change this merit order. For example, a higher electricity price would be to the disadvantage for oxyfuel combustion. Furthermore, when implementing a CO2 tax, CCS is deployed at a later period compared to the CO2-Cap scenarios, which leads to a lower share of post combustion technologies in the technology mix. The analysis of the CCS technologies also indicates that calcium looping is not economically competitive under the assumptions made in appendix A2.5.

### 3.3. Material flows

With the newly developed methodology described in section
2.1, an analysis of the material flows becomes possible. A sensitivity analysis is performed to investigate the deployment of the recycling paths (Fig. 4). In the BAU scenario, raw material consumption remains stable, but due to the decreasing clinker content in cement, the usage of limestone for cement production decreases. Consequently, the usage of limestone and other materials as SCM’s increases. On the other hand, the available demolished concrete as SCM is expected to increase (Bundesamt für Umwelt (BAFU), 2015), which remains unused in the BAU scenario.

The raw materials demand with and without usage of demolished concrete in the BAU is shown in Fig. 12. Because of the relatively low CO$_2$ emissions and the relatively low energy consumption of the limestone mining and the crushing of demolished concrete, the results are very similar for all the scenarios. The sensitivity analysis shows, that only a very low premium (around 2 EUR/t) is needed for demolished concrete to become economically attractive as a SCM. This indicates that the use of recycled demolished concrete can become economically beneficial, under the...
assumption that it will be technically feasible from 2030. Re-using demolished concrete as clinker substitute has a significant influence on the cement properties, which is neglected in this study. A cement type in which recycled concrete is the only SCM is not realistic from a technical perspective. Nevertheless, it shows the theoretical potential for recycled concrete in the cement production. How the demolished concrete is recycled (e.g., as gravel) or whether it goes to landfill is not part of this analysis. However, if the demolished concrete can be used as a SCM, the raw material consumption (especially limestone) decreases as well as the amount of waste concrete used for other purposes. This would make concrete production more material efficient. The analysis shows the maximum theoretical potential. In this case, limestone consumption would decrease by 2050 by 30%, which would help to use the remaining accessible limestone resources in an efficient way. Substituting burned shale and gypsum as a SCM is less advantageous from a material efficiency perspective, as both are waste products of other industrial processes. However, they might not be available in future if industry changes.

Another recycling option for concrete in cement plants is the carbonation of concrete waste. Our model results show that it is not economic to reuse calcium carbonate as a raw material in the cement production as long as there is enough limestone available. Nevertheless, high purity calcium carbonate can be produced through carbonation and sold on the market as a separate product. According to our analysis, the market price for high purity calcium carbonate should be at least be in the range of 60–80 EUR/t CaCO₃ (depending on the scenario and the availability of captured CO₂) for waste concrete carbonation to become economically attractive from 2030.

4. Discussion

4.1. Emissions accounting

In this study, all CO₂ emissions from fuel combustion are accounted to the cement sector which is defined as gross emissions in (Cement Sustainability Initiative (CSI), 2011). If CO₂ emissions from burning residential waste were to be allocated to the residential sector rather than the cement sector (representing net emissions in (Cement Sustainability Initiative (CSI), 2011)), it would give the cement sector an inducement to reduce its emissions by fuel switching. At the same time, the residential sector would have additional incentives to reduce residential waste. The second allocation problem is the allocation of CO₂ emissions when feeding waste heat into the district heating network. In this study, there are no CO₂ emissions transferred from the cement sector to the residential sector when district heat is passed on. However, using waste heat to supply heat to the district heat is an option to improve the energy efficiency of the cement plants. These cross-sectoral dynamics can be captured through our future analysis on full sector coupling in STEM.

4.2. Production capacity

With the decreasing clinker ratio, the total kiln capacity in Switzerland decreases. There will most likely not be as many cement plants needed in the future to produce the same amount of cement. In the model, the least energy efficient kilns are retired even before they reach the end of their lifetime.

4.3. Cement demand

The cement production costs increase by approximately 30% in 2050 in order to reach zero emissions in the cement sector in the CAP-100 scenario compared to the BAU scenario. Such an increase would be expected to reduce cement demand, increase costs in cement-using sectors, or both. However, all demand-side and economic impacts are neglected in this study.

4.4. Result scope

Although, this analysis focusses on the Swiss cement industry, many of the results can also be transferred to other countries, even
though the existing stock may differ. The use of alternative fuels and clinker substitution can help reducing the energy use and improving the environmental performance in any country. Analyzing Fig. 2 indicates, that the potential for replacing clinker with SCM’s and replacing coal with alternative fuels is high in both, the European cement industry as well as in the global cement industry. This is also shown in the roadmap until 2050 of the European cement industry (Cembureau, 2019). Furthermore, the potential for energy efficiency improvement might be even higher in some countries compared to Switzerland, as the Swiss cement industry already belongs to the most energy efficient cement production sites in the world. Especially production facilities which use the more energy intensive wet process have a significantly higher energy efficiency improvement potential. The Swiss pathway for CCS can be adopted to developed countries, where the production capacity of clinker is not expected to increase in the near future. On the other hand, the case is different for developing countries that have other options for CO₂ abatement, because new cement plants with the latest technologies are still built. This strongly enables possibilities new technologies (eg. oxyfuel combustion, hydrogen usage) that are difficult to implement retrofitting the existing plants in developed industries.

5. Conclusion

In this study, we analyze energy efficiency and CO₂ mitigation of the Swiss cement sector with a long-term perspective under various energy and climate policies including scenarios aiming at net zero CO₂ emissions in 2050. With a technology-rich techno-economic energy system modeling approach, that includes energy and material flows, as well as energy and process-related CO₂ emissions, we performed a scenario analysis addressing several policy measures versus a business as usual (BAU) development. Our results show that future cement production improves its energy efficiency and decreases its CO₂ emissions even without major policy intervention mainly due to the decreasing clinker content in cement and deployment of more efficient technologies (to replace existing technologies). This is because many energy efficiency measures become economically optimal in a long-term perspective under our fuel price assumptions. Although applying a CO₂ tax up to 60 EUR/tCO₂ results in a more expensive cement production, the total CO₂ emissions will not be reduced significantly. According to our cost assumptions, a CO₂ tax above 60 EUR/tCO₂ makes it economically attractive to reduce CO₂ emissions using CO₂ capture technologies with the benefit of avoiding both energy and process related CO₂ emissions. No significant reduction of the CO₂ emissions is possible in cement production without CO₂ capture and the corresponding infrastructure to transport and sequestrate CO₂. Therefore, the cement sector relies heavily on the development of these technology applications. Deployment of CO₂ capture will increase the specific electricity consumption of the cement industry. From an economic point of view, fuel switching from coal to natural gas or alternative fuels is only a limited option to decrease the CO₂ emissions of the cement industry because of the high share of process related emissions (approximately two thirds) and limitations with regards to switching of burner technologies in the complex process setting of a cement plant.

CRediT authorship contribution statement

Michel D. Obrist: Conceptualization, Methodology, Validation, Investigation, Writing - original draft, Visualization, Project administration. Ramachandran Kannan: Conceptualization, Resources, Writing - review & editing, Supervision. Thomas J. Schmidt: Supervision, Writing - review & editing. Tom Kober: Conceptualization, Resources, Writing - review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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