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Decarbonizing the cement industry: Findings from coupling prospective life cycle assessment of clinker with integrated assessment model scenarios

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ABSTRACT

In the race to achieve global climate neutrality, carbon intensive industries like the clinker and cement industry are required to decarbonize rapidly. The environmental impacts related to potential transition pathways to low-carbon systems can be evaluated using prospective life cycle assessment (pLCA). This study conducts a pLCA for future global clinker production, integrating long-term transition pathways from the IMAGE integrated assessment model (IAM) to maintain global consistency. It systematically modifies the ecoinvent v3.9.1 database using the Python library *premise* to create future database versions representing future clinker production embedded in a future economy according to a 3.5°C-baseline, a 2°C-compliant and a 1.5°C-compliant scenario. Our study indicates that climate change impacts of clinker production may decrease from about 1.03 kg CO_2-eq/kg clinker in 2020 to 0.94 (3.5°C-baseline), 0.20 (2°C-compliant), and 0.16 (1.5°C-compliant) kg CO_2-eq/kg clinker in 2060 for the global average. This corresponds to a 10% (3.5°C-baseline), 81% (2°C-compliant) and 84% (1.5°C-compliant) decrease by 2060 compared to 2020. Under these scenarios, global clinker production alone would require 5%–11% of the remaining end-of-century carbon budget for the 2 °C and 1.5 °C-target, respectively. While the climate change impacts are substantially reduced, our study also indicates that the transition pathways shift the burden towards other impact categories, such as ionizing radiation, ozone depletion, material resources and land use. Developing IAM-compatible scenarios for more product groups helps to increase the coherence of pLCA studies. As this study is based on an IAM heavily reliant on carbon capture and storage and bioenergy, future research should explore the effects of different technology pathways and alternative mitigation strategies.

1. Introduction

Cement contributes 8% of global energy-related greenhouse gas (GHG) emissions (IEA, 2021). Meeting the Paris Agreement targets requires rapid decarbonization of cement production (Benhelal et al., 2021). Amid these growing climate concerns, numerous decarbonization strategies have been proposed by the cement industry itself (Cembureau, 2012, 2013, 2020; GCCA, 2021; VDZ, 2020), NGOs (Cao et al., 2021; Friedrichsen et al., 2018; IEA, 2009, 2018; New Climate Institute, 2020; Ruppert et al., 2020), and academia (Favier et al., 2018; Fennell et al., 2022; Wei et al., 2019). Measures include improved energy efficiency and fuel switch (Favier et al., 2018; Georgiopoulou and Lyberatos, 2018; Leilac, 2021b) and carbon capture and storage (CCS) technologies (Favier et al., 2018; Leilac, 2021b; Voldsund et al., 2019). Replacing clinker with supplementary cementitious materials (SCMs) (Kermeli et al., 2019) or non-limestone-based binders (Favier et al., 2018; Miller and Myers, 2020) are other options, although their mitigation potential is limited or niche. Other downstream measures include reduced cement and concrete use, material substitution, reuse, and carbonation (Favier et al., 2018; GCCA, 2021).

Existing studies on the environmental impacts of future cement production indicate significant reduction potentials for GHGs. Yet, the results are difficult to compare due to different assumptions on included

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Abbreviations

BAT	Best available technology
BECCS	Biomass energy with carbon capture and storage
CCS	Carbon capture and storage
CF	Characterization factor
CTC	Clinker-to-cement
DS	Direct separation
GCCA	Global Concrete and Cement Association
IAM	Integrated assessment model
IEA	International Energy Agency
IMAGE	Integrated Model to Assess the Global Environment
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LCI	Life cycle inventory
GHG	Greenhouse gas
GWP	Global warming potential
MEA	Mono-ethanolamine
pLCA	Prospective life cycle assessment
RCP	Representative Concentration Pathways
SCM	Supplementary cementitious materials
SEC	Specific energy demand
SSP	Shared Socioeconomic Pathway

technologies, life cycle stages, scenario parameters, and regional and temporal coverage. Work on future decarbonization of cement, like that of Zhang et al. (2018) does not include disruptive technological change, while that of Obrist et al. (2021) lacks a life cycle approach and covers only a single country (i.e., Switzerland). Georgiades et al. (2023) conducted a comprehensive prospective life cycle assessment (pLCA) of cement production on a European scale, yet used literature-based rather than coherent macroeconomic scenarios for cement. Although the seminal work by Sacchi et al. (2021) includes coherent macroeconomic pathways for the cement sector, it has limitations in modeling specific fuels and production technologies. It also lacks a comprehensive analysis of the global and sectoral implications. In addition, these studies consider climate impacts as their core object of analysis, with little attention to the impacts on other environmental compartments, which are under similar pressure as the climate system (Richardson et al., 2023).

Life cycle assessment (LCA) is a method for quantifying different environmental impacts of a product over its life cycle. It is commonly used to evaluate and compare existing technology alternatives and to identify impact trade-offs and hotspots (European Committee for Standardization, 2006a; 2006b). The life cycle thinking approach encapsulates direct (scope 1) and embodied (scope 2 and 3) emissions. Prospective LCA (pLCA) focuses on future impacts using scenarios to explore potential developments (Langkau et al., 2023). However, these scenarios are usually developed separately for individual products or sectors. As a result, they show little harmonization between studies and often fail to consider spillover effects between systems (Arvidsson et al., 2018; Guinée et al., 2018; Sacchi et al., 2021; van der Giesen et al., 2020). Coupling pLCA with integrated assessment models (IAMs) helps to overcome the limitations of isolated, incompatible scenarios. It provides a robust approach to assessing the future environmental impacts of entire sectors under uncertainty. Integrated assessment models are large-scale computational tools that simulate how human activities influence long-term environmental change. They provide a holistic view of the macro-level implications of different decarbonization pathways, considering elements such as policy impacts and carbon taxes, interaction between economic sectors, and interaction with the environment (Hausfather, 2018; O'Neill et al., 2014; Pauliuk et al., 2017; Stehfest et al., 2014; van Vuuren et al., 2011). The climate change impacts of IAM pathways have been assessed previously for the cement industry (Edelenbosch et al., 2017; van Ruijven et al., 2016; van Sluisveld et al., 2021), but lack the inclusion of (future) embodied emissions through a (prospective) life cycle perspective. Previous research on coupling pLCA with IAMs has focused mainly on the energy and electricity sector (Cox et al., 2018; García-Gusano et al., 2015; Gibon et al., 2015; Hertwich et al., 2015; Mendoza Beltran et al., 2018), with recent advances in multi-sector coupling with the tool premise (Sacchi et al., 2021).

This study assesses the potential future environmental impacts of decarbonization pathways for global clinker production until 2060 in a fully transparent, easy-to-reproduce prospective life cycle assessment set-up coupled with the global IMAGE integrated assessment model. This study focuses on clinker production, the emission hotspot in cement. To achieve macroeconomic coherence, we integrate internally consistent and technically feasible scenarios for global clinker production and global scenarios for other sectors. This allows us to assess the long-term and large-scale implications of the transformation pathways while understanding the detailed impacts at the process level (Arvesen et al., 2018). In the following sections, we will describe the applied methodology (section 2) and results (section 3) and discuss findings in more detail (section 4) before concluding (section 5).

2. Method

2.1. Goal and scope

This study compares global clinker production's future environmental impacts, hotspots, and burden shifts. It is an attributional and prospective LCA covering 2020 to 2060. The functional unit is 1 kg of clinker. It has a global scope, divided into the 26 world regions of IMAGE. The scope is cradle-to-gate, including the mitigation options considered in IMAGE, as described in section 2.2.2. Other cradle-to-gate mitigation options, such as alternative binders (Miller and Myers, 2020), kiln electrification (Wilhelmsson et al., 2018), and measures during cement use and end-of-life phase, are not considered. The characterization methods of the EF3.0 impact assessment method (Fazio et al., 2018) are used for all impact categories, except for climate change impacts, for which the IPCC 2021 GWP 100a method is used (IPCC, 2021). See Table A3 for an overview of impact categories used. The GWP100a method calculates the global warming potential (GWP) of various greenhouse gases, comparing their ability to trap heat over a century against CO_2, which has a GWP of 1. This approach makes it possible to evaluate gases such as methane (CH_4), which has a higher GWP despite its shorter lifespan due to its more effective ability to trap radiation in the short term (IPCC, 2021). Additional characterization factors (CFs) for biogenic CO_2 flows and hydrogen emissions are added to the global warming (GWP100a) midpoint indicator: 1, +1, and +11 kg CO_2-eq per kg of biogenic CO_2 uptake and release and hydrogen emissions (Sand et al., 2023), respectively (see Table A2). These additional CFs are essential for assessing future industrial systems, where net negative emission technologies and hydrogen supply chains play a role (Sacchi et al., 2021). The life cycle inventory (LCI) database ecoinvent v3.9.1 cut-off (Wernet et al., 2016) is used and modified with the prospective database modification tool *premise* (Sacchi et al., 2021). We use the LCA software *Brightway2* (Mutel, 2017) in combination with *Activity Browser* (Steubing et al., 2020) and the superstructure approach (Steubing and Koning, 2021) for LCA calculations and interpretation.

2.2. Scenario development

The prospective scenarios used in this study are based on the IMAGE

(Integrated Model to Assess the Global Environment) IAM (Stehfest et al., 2014). Among the existing IAMs, IMAGE is notable for its detailed representation of the cement industry (Gambhir et al., 2019; Keppo et al., 2021; Stehfest et al., 2014; van Ruijven et al., 2016; van Sluisveld et al., 2021). As a process-based IAM, IMAGE is particularly strong in representing physical flows at high regional and sectoral resolution, but is less suitable to explore economic drivers, see appendix A section 1. The scenarios cover the Shared Socio-economic Pathway 2 (SSP2), also called *middle-of-the-road* (Riahi et al., 2017), combined with three Representative Concentration Pathways (RCPs): no climate policy (RCP-Base) (3.5 °C), RCP-2.6 (2 °C) and RCP-1.9 (1.5 °C). The study integrates the technological changes in clinker production projected by IMAGE, see section 2.2.2. In addition to IMAGE-compatible foreground scenarios for clinker, background scenarios for other major industrial sectors and emitters (electricity, steel, fuels, transport, non-CO_2 emissions, and CCS) have been included using *premise* (Sacchi et al., 2021). A simplified flowchart of the model is shown in Fig. 1.

2.2.1. Technology coverage

This study considers the following clinker production technologies included in IMAGE: standard (rotary) kiln, efficient kiln, kiln with mono-ethanolamine (MEA) CCS, Oxy CCS, and Direct Separation (DS) CCS, see flowcharts in Fig. 2. Details on energy consumption, emissions, and CO_2 capture rates are given in Table A4.

The standard kiln represents the regional average mix of all currently used kiln types. The efficient kiln represents the best available technology (BAT) of a 6-stage pre-heater and pre-calciner kiln, which is assumed to be installed if a new kiln without CCS is built. Three different CCS technologies are considered. MEA CCS is a retrofit option that uses mono-ethanolamine (MEA) for CO_2 absorption with a 90% CO_2 capture rate. The heat required for MEA regeneration (4.06 MJ/kg CO_2) is modeled in this study with the same thermal heat mix as the kiln, while it has been modeled in previous studies with natural gas boilers (Voldsund et al., 2019). CO_2 emissions from this heat supply are also captured in our model. In Oxy CCS kilns, fuel combustion and limestone calcination occur in pure oxygen and CO_2 instead of air. This results in a cleaner flue gas stream, from which CO_2 can be directly captured with a 90% CO_2 capture rate (Voldsund et al., 2019). With direct separation (DS) CCS, the raw materials are indirectly heated in a steel pre-heater, which avoids mixing the pure process flue gases with the less pure combustion flue gases. DS CCS captures 95% of the CO_2 from process emissions, with a lower energy penalty due to the purity of the process flue gas (Leilac, 2021a). Yet, DS CCS does not capture fuel-related CO_2 emissions, so its overall capture efficiency is only modest (55–60%). Other CCS technologies, such as chilled ammonia and calcium tail looping, are not included because they lack representation in IMAGE. The techno-economic analysis for Switzerland by Obrist et al. (2021) also found that in scenarios with large-scale CCS deployment, MEA and Oxy CCS are adopted, while the other CCS technologies, including chilled ammonia and calcium looping, have negligible shares.

The ecoinvent process “clinker production, Europe without Switzerland” is the basis for all modeled kilns, with adjustments to reflect the kiln-specific differences, summarized in Table A4-5 and visualized in Fig. A2. The specific energy demand (SEC) in the starting year (2020) for conventional kilns is taken from the average regional SEC reported by the Global Concrete and Cement Association (GCCA) (GCCA, 2019), see Fig. A1. Efficient kilns and kilns with CCS are assigned SEC_{2020} from BAT reports (Schorcht et al., 2013). The additional energy demand and carbon capture rates for CCS kilns are taken from pilot studies on the respective technologies (Leilac, 2021a; Voldsund et al., 2019). Abated and unabated CO_2 emissions are calculated stoichiometrically from the SEC, fuel mix, and carbon capture rate per kiln type, region, year, and scenario, see Table A4. Purified CO_2 transport and storage are modeled based on Sacchi et al. (2021), using a conservative transport distance (400 km) and storage depth (3 km). Appendix B contains the full LCIs.

2.2.2. Foreground scenario construction

The foreground scenarios are based directly on the IMAGE v3.3 scenario results. Figs. 3 and 4 summarize the main characteristics of the IMAGE clinker variables and how they are integrated into the LCA model.

Process regionalization: In all scenarios, the prospective kiln inventories are regionalized for all 26 IAM world regions listed in Fig. A3 and Table A7. Total clinker production is stable at around 3 Gt/year, but there is a shift between regions, see Fig. 4a.

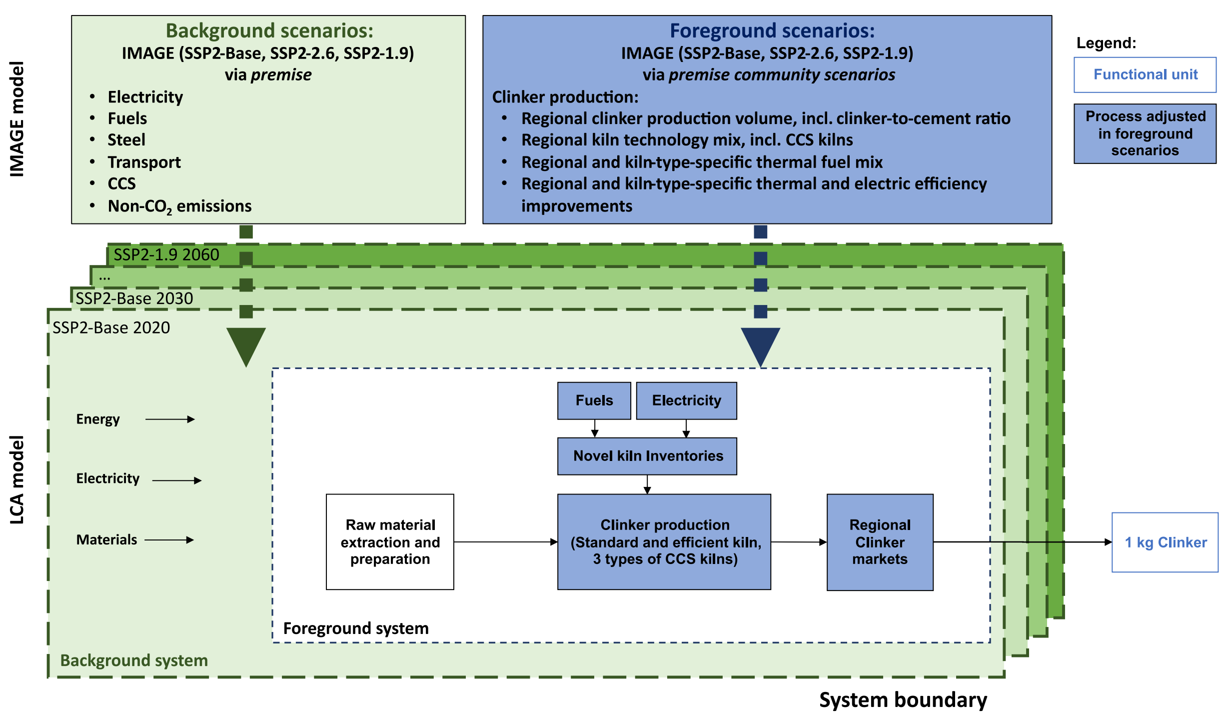

Fig. 1. Simplified flowchart of the product system and model integration.

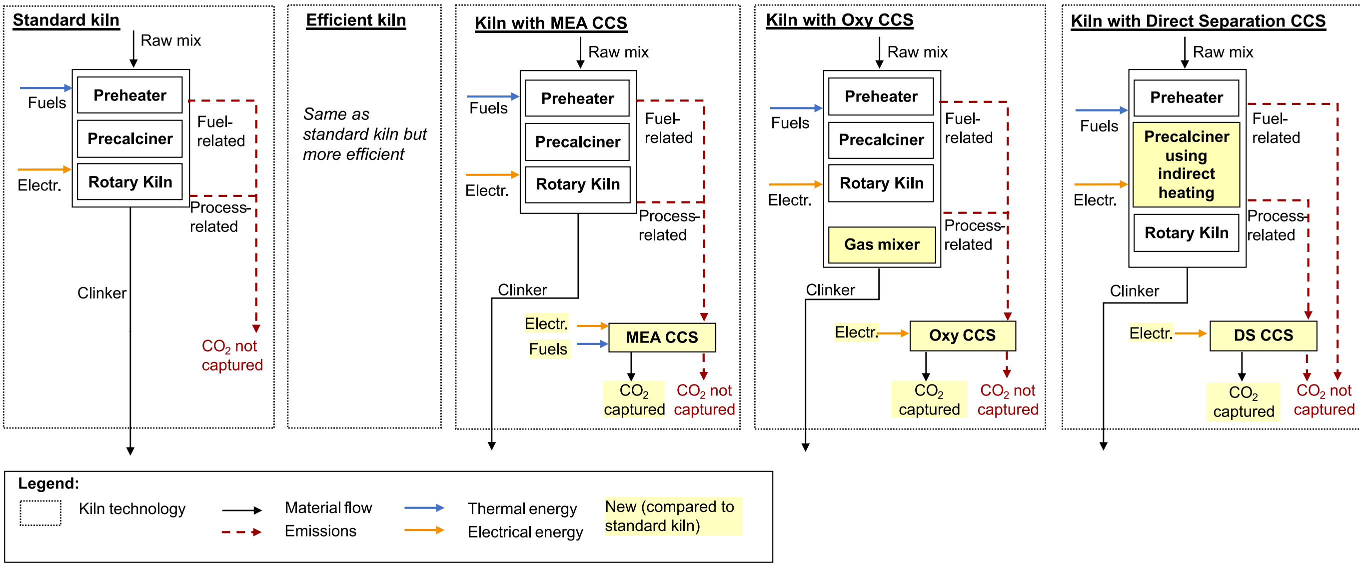

Fig. 2. Flowchart of clinker kilns used in this study.

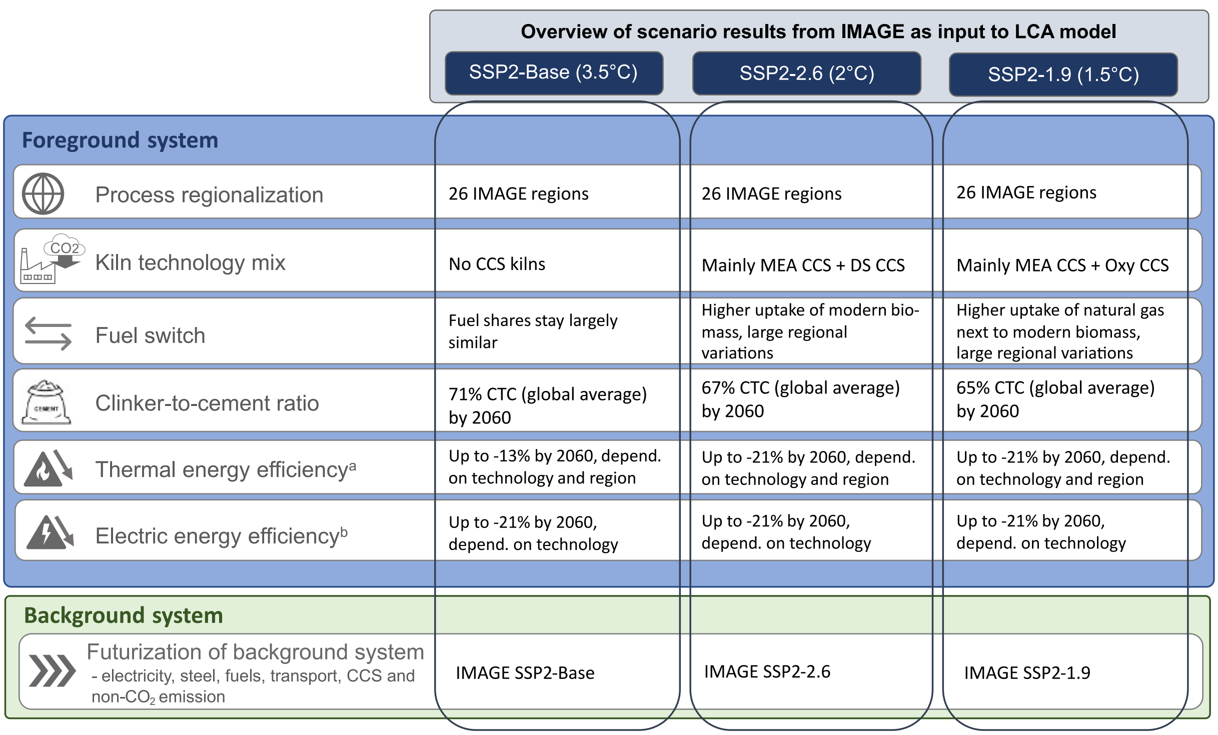

Fig. 3. Scenario results from IMAGE used in this study and their implications in the different scenarios. [a] Thermal energy efficiency from IMAGE undergoes corrections documented in Figs. A5–6, [b] electric energy efficiency is taken directly from IMAGE model documentation; see Table A9.

Kiln technology mix: Standard kilns remain the leading technology in the baseline scenario, and no CCS kilns are implemented. In SSP2-2.6 (2 °C), MEA CCS kilns and, to a lesser extent, DS CCS kilns dominate production. In SSP2-1.9 (1.5 °C), MEA CCS kilns also gain the highest shares, followed by Oxy CCS, while DS CCS has only negligible shares. In both climate-ambitious scenarios, the first CCS kilns enter the market between 2025 and 2030, see Fig. 4b.

Fuel mix: IMAGE considers eight fuel types: coal, natural gas, oil, electricity, secondary heat, traditional biomass, modern biomass, and hydrogen. Traditional biomass, secondary heat, and hydrogen are used at negligible levels in very few regions and years. The global fuel mix per scenario is shown in Fig. 4c, and further disaggregation by kiln type is shown in Fig. A4. IMAGE considers the fuel use for the entire non-metallic mineral sector, which is taken as a proxy for the cement industry. Table A8 describes the mapping of IMAGE fuel categories to processes in ecoinvent v3.9.1.

Clinker-to-cement (CTC) ratio: The CTC ratio decreases from 80% in 2020 to 71% (SSP2-Base), 67% (SSP2-2.6), and 65% (SSP2-1.9) in 2060, see Fig. 4a. This modest reduction is motivated by a lower additional replacement potential of SCMs due to their limited future availability. The CTC ratio does not influence the environmental impact results per kg clinker but affects total emissions by defining the overall amount of clinker needed.

Energy efficiency: The future regional- and technology-specific

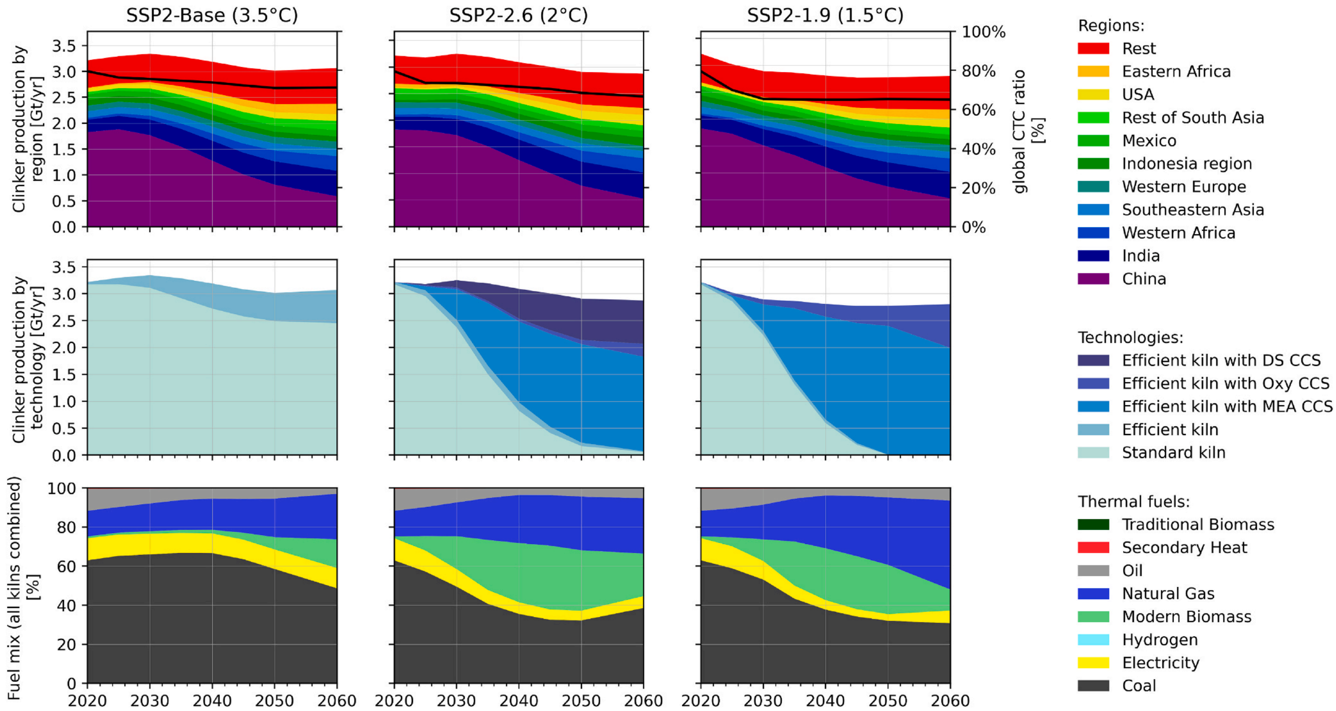

Fig. 4. Foreground scenarios from IMAGE: clinker production by region (a) and by technology (b), and fuel mix for all kilns combined (c) in the scenarios SSP2-Base, SSP2-2.6, and SSP2-1.9. CTC = clinker-to-cement.

thermal efficiency increase compared to 2020 is modeled based on IMAGE, with some minor data corrections documented in Figs. A5–6 and Table A9. It should be noted that only SEC of the kilns is reduced, not SEC of supporting processes, such as absorbent regeneration for MEA CCS kilns. As the electrical energy efficiency could not be separated from the thermal energy efficiency due to joint reporting in the IMAGE data, electrical efficiency gains were based on the IMAGE documentation (van Ruijven et al., 2016). As with thermal energy efficiency, electrical efficiency improvements only include the electricity consumption at the kiln level and exclude additional processes.

3. Results

3.1. Climate change impacts

The climate change results in this study are shown for different levels of the system: for the level of the individual technologies and for the level of regional and global clinker markets, which contain different market shares of the technologies.

Fig. 5 shows the climate change impacts of producing 1 kg of clinker by different Western European kilns in 2020, 2040, and 2060 for the 2 °C scenario. Results for the base and 1.5 °C scenario are provided in Fig. A7. Clinker produced in other regions shows slightly different absolute values due to the regionalization of processes, but the trends are similar. Process emissions (i.e., limestone calcination) have the most significant contribution for all Western European kiln types, with 0.54 kg CO_2/kg clinker, followed by fuel-related emissions. This means that direct emissions (calcination and fuel combustion at the kilns) make up most of the climate change impacts for kilns without CCS. In contrast, indirect emissions contribute little, including electricity and all other processes.

The CCS kilns' lower direct and lower net emissions are due to the negative emissions from capturing carbon at the kiln. Due to the additional energy demand for MEA regeneration, kilns with MEA CCS kilns have a higher energy demand, higher CCS requirement, and higher net CO_2-eq emissions per kg of clinker than Oxy kilns. DS CCS kilns only capture 95% of the process-related emissions and none of the combustion-related emissions, resulting in a higher overall CO_2 footprint. For kilns with CCS, the share of indirect emissions (energy

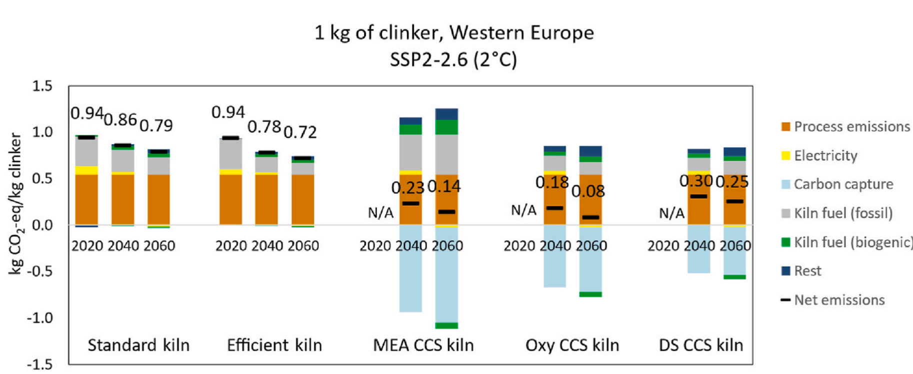

Fig. 5. Climate change impacts of producing 1 kg clinker from the different kilns for the Western Europe region in SSP2-2.6 (2 °C) in 2020, 2040, and 2060. The impact category used is IPCC 2021 GWP100a with additional biogenic carbon and hydrogen characterization factors based on Sand et al. (2023). N/A means this kiln type is not implemented for Western Europe in the respective scenario and year.

consumption at the CCS processes, electricity, and all other processes) in the total emissions is proportionally higher than for kilns without CCS.

Our model builds regional markets based on the technology uptake projected by IMAGE. For the ten largest regional clinker markets and the world average, Fig. 6 shows the development of climate change impacts over time. In 2020, the world average was 1.03 kg CO_2-eq/kg clinker for all scenarios. In the SSP2-Base scenario, the climate change impact decreases only slightly by 9%, reaching 0.94 kg CO_2-eq/kg clinker in 2060. The 2°C-compatible scenario exhibits a significant reduction of 81% to 0.20 kg CO_2-eq/kg clinker in 2060. The SSP2-1.9 (1.5 °C) scenario reduces emissions only slightly further to 0.16 kg CO_2-eq/kg clinker in 2060, achieving a decrease of 84%. CO_2 emission reductions occur earlier in SSP2-1.9 (1.5 °C) than in SSP2-2.6 (2 °C).

Western Africa and Indonesia achieve carbon-negative clinker production in some years due to the combined use of CCS and biomass energy, both in clinker production and in the background electricity mix that relies on biomass energy with subsequent carbon capture and storage (BECCS). The climate change impact results are higher, e.g., 17% higher impact in 2060 in SSP2-2.6, than those without additional CFs for biogenic carbon and hydrogen (shown in Appendix Fig. A8). This is because there is more release than uptake of biogenic carbon across the supply chains in the model, which results in a net addition of GWP from biogenic carbon to the results of the standard IPCC 2021 GWP100a method. The new CFs for hydrogen do not contribute to the results. This underlines the importance of accounting for the warming related to biogenic carbon in systems with a high proportion of biogenic fuels.

Fig. 7 shows the climate change impacts of all 26 regional clinker markets for the baseline scenario in 2020 and for all three scenarios in 2060. The decarbonization trends in the climate-ambitious scenarios are evident in all regions. However, regional differences in the choice of kiln technology and thermal fuels (pie charts in Fig. 7) and other modeling parameters lead to different results.

3.2. *Burden shift in impacts of future clinker production*

Fig. 8 shows the potential environmental impacts of 1 kg clinker from the world market for all environmental impact categories used in this study from 2020 to 2060. The results are normalized by the impacts for the year 2020 (purple circle) and presented on a logarithmic scale. The absolute values are shown in Table A10 in Appendix A. Fig. A10 shows the temporal development for all impact categories for the ten largest regional markets.

The scenarios with climate targets (2 °C and 1.5 °C) lead to future burden shifts between potential environmental impacts, while the impacts do not change considerably in the baseline scenario. The shifts in impacts are more pronounced in the 1.5 °C than the 2 °C scenario and become more prominent over the years in both scenarios. The only pronounced changes in the baseline scenario occur for ionizing radiation, caused by a reduction of nuclear energy, and for particulate matter, which is caused by reduced emissions from coal power generation. For SSP2-2.6 (2 °C) and SSP2-1.9 (1.5 °C), the most pronounced decrease is seen in climate change impacts described in the previous section. Additionally, acidification reduces in the climate-ambitious scenarios due to the phase-out of conventional kilns and the introduction of CCS kilns, which have lower NO_x and SO_x emissions due to advanced filtration of flue gases. Fewer phosphate emissions from mining waste treatment in coal mining reduce freshwater eutrophication. Reductions in marine eutrophication are similar to acidification, mainly attributed to the reduced NO_x emissions when moving to CCS-based kilns. Particulate matter is reduced due to reduced electricity production from coal. Ozone depletion increases substantially over time due to methane emissions and refrigerant gases (i.e., halon) during the extraction and distribution of natural gas. However, because these refrigerant gases will be phased out in the future by the Montreal Protocol (Heath, 2017), these impacts are almost certainly an overestimate. Material resource depletion worsens due to a higher demand for metals like copper. Land-use impacts increase due to the shift to bio-based energy carriers for clinker production and power generation. Ionizing radiation increases because of more nuclear power. In tropical regions, water use increases due to more hydropower electricity (i.e., freshwater evaporation).

3.3. *Contribution of clinker scenarios and scenarios of other sectors*

The contribution of foreground and background scenarios to the reductions in climate change impact is shown in Fig. 9 for 1 kg clinker from the world market. While most impact reduction stems from the foreground clinker scenarios, approximately a third comes from the decarbonization of the background electricity system. This observation is logical since the climate-ambitious scenarios contain more CCS kilns, which have proportionally larger shares of embedded emissions caused by the energy- and electricity-intensive carbon capture processes. For future kiln fleets with high CCS shares, decarbonizing the electricity grid in the background becomes a significant lever, next to reducing direct emissions. This shows that joint modeling of foreground and background systems is essential to capture the ripple effects across the supply chain and to avoid a temporal mismatch (Arvidsson et al., 2018). For clinker, only changes in the background electricity sector have a significant contribution. However, changes in other background sectors may become influential for products with a more complex supply chain. Thus, evaluating the overlayered scenarios separately and analyzing the contribution of foreground and background changes is also essential. This calls for further guidance concerning requirements for modeling and communicating scenarios in pLCA, as Bisinella et al. (2021) put forward.

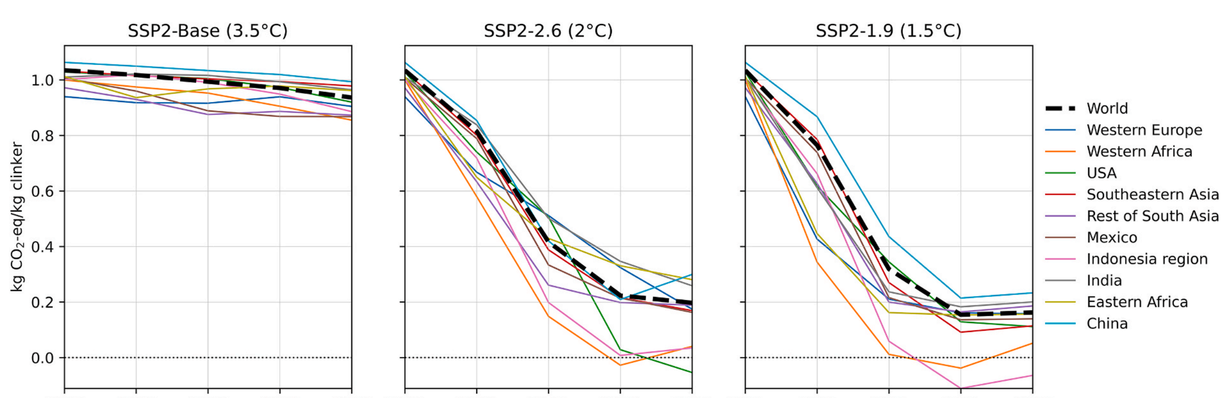

Fig. 6. Impacts on climate change for 1 kg clinker from the world market and the ten largest regional markets for the three scenarios. The impact category used is IPCC 2021 GWP100a with additional biogenic carbon and hydrogen characterization factors based on Sand et al. (2023).

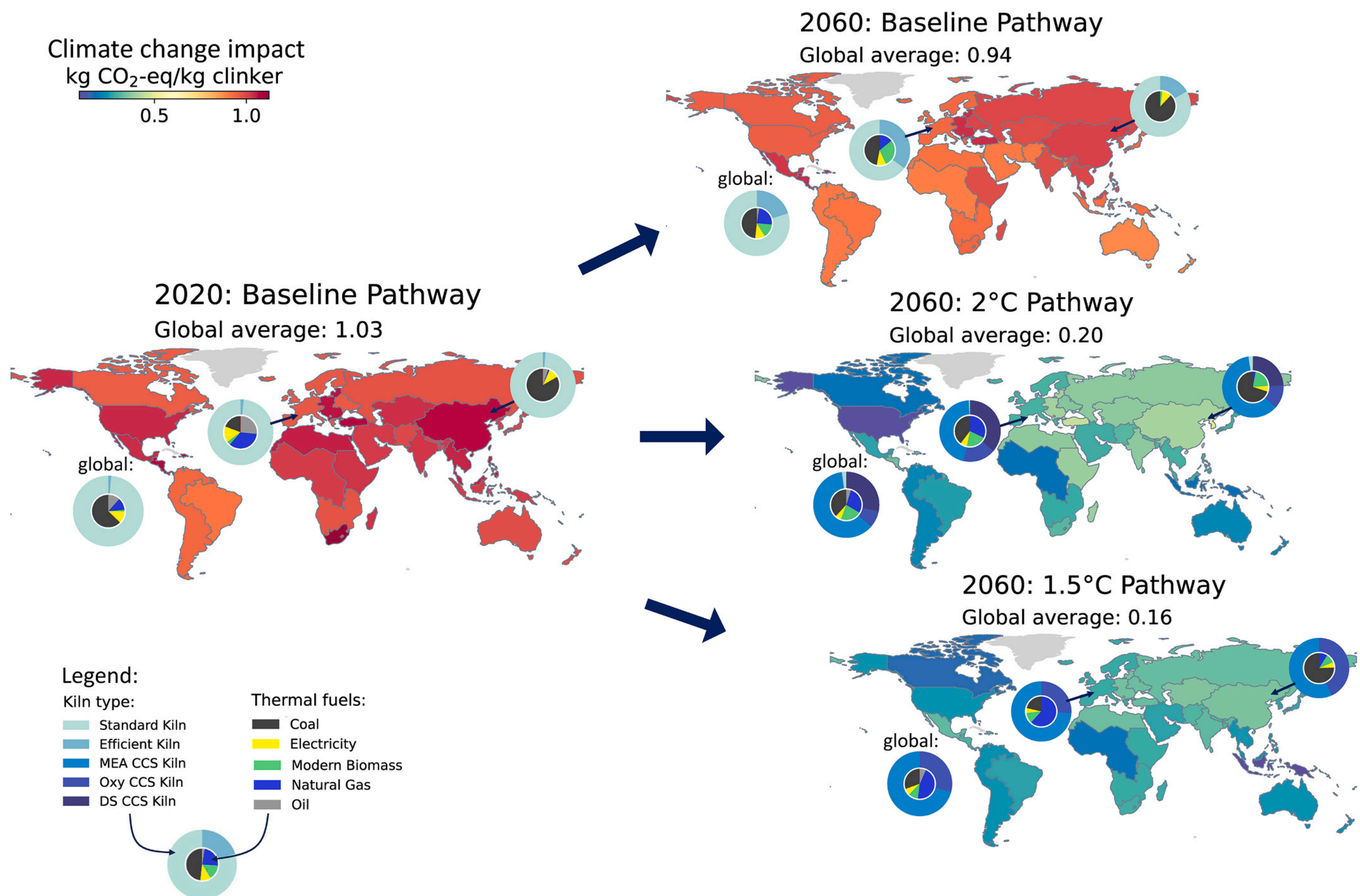

Fig. 7. Climate change impacts of 1 kg clinker from 26 regional markets for current production (2020, SSP2-Base (3.5 °C)) and production in 2060 in the SSP2-Base (3.5 °C) and SSP2-2.6 (2 °C), SSP2-1.9 (1.5 °C) scenarios. Outer pie charts show kiln shares and inner pie charts show the thermal fuel mix. They are provided for the global average, and Western Europe and China are examples.

3.4. Cumulative impacts on climate change

Fig. 10 shows global clinker production's annual and cumulative life cycle GHG emissions. Annual emissions amounted to 3.33 Gt CO_2-eq in 2020. While the baseline scenario sees only a slight decrease to 2.87 Gt CO_2-eq/year by 2060 (−16%), SSP2-2.6 and SSP2-1.9 scenarios achieve more significant reductions to 0.57 Gt CO_2-eq/year (−83%) and 0.46 Gt CO_2-eq/year by 2060 (−86%), respectively. Notably, residual emissions persist in 2060, even in the low-carbon clinker scenarios. Concerning kiln types, the residual GHG emissions almost exclusively originate from standard kilns, contributing to 88% of cumulative GHG emissions in SSP2-Base, 74% in SSP2-2.6, and 77% in SSP2-1.9. In comparison, their cumulative production volume amounts to 88% (SSP2-Base), 41% (SSP2-2.6), and 39% (SSP2-1.9), respectively. Thus, most future GHG emissions stem from legacy kilns despite their low future production volumes in SSP2-2.6 and SSP2-1.9 since CCS kilns capture most direct CO_2 emissions and, thus, effectively cut overall emissions compared to standard kilns. This result emphasizes the urgency to overcome lock-ins in carbon-emitting clinker production infrastructure to meet climate goals.

The cumulative GHG emissions from global clinker production between 2020 and 2060 are projected at 129 Gt (SSP2-Base), 67 Gt (SSP2-2.6), and 56 Gt (SSP2-1.9), see black line in Fig. 10. The Intergovernmental Panel on Climate Change (IPCC) estimates the remaining carbon budget from 2020 until the end of the century for a 50% likelihood of staying below 2 °C and 1.5 °C at 1350 Gt and 500 Gt, respectively (IPCC, 2021). Thus, the global clinker industry between 2020 and 2060 would take up 5% of the remaining carbon budget for this century in the 2°C-compatible scenario and 11% in the 1.5°C-compatible scenario.

3.5. CCS demand of the global clinker production

Most reductions in climate change impacts in the presented scenarios are achieved by switching to kilns with CCS. Fig. 11 shows the study's yearly and cumulative CCS requirements of the global clinker industry. In SSP2-Base, no CCS technologies are adopted. Both scenarios with CCS show similar yearly CCS capacities by 2060 (SSP2-2.6: 2.32 Gt CO_2/year, SSP2-1.9: 2.37 Gt CO_2/year), but the 1.5°C-compatible scenario requires a slightly faster CCS uptake than the 2°C-compatible scenario. The cumulative requirement for long-term storage of the captured CO_2 in the clinker industry is shown by the black line in Fig. 11. Between 2020 and 2060, 61.6 Gt of cumulative CO_2 storage is needed globally in SSP2-2.6 and 65.4 Gt in SSP2-1.9. Regarding regional distributions, China, India, and Western Africa are projected to have the highest CO_2 storage demand, accounting for 53% (SSP2-2.6) and 55% (SSP2-1.9) of the cumulative CO_2 storage required globally.

It is interesting to see that SSP2-2.6 has a very similar total CCS demand as SSP2-1.9 (only 6% lower than SSP2-1.9) but considerably higher cumulative CO_2-eq emissions (20% higher than SSP2-1.9). This is caused by the interplay of the following reasons: i) slightly higher demand for clinker in SSP2-2.6 (see Fig. 4a); ii) a higher uptake of DS CCS kilns in SSP2-2.6, which have a lower CO_2 capture rate than the other CCS technologies; and iii) no uptake of Oxy CCS kilns in SSP2-2.6, which has the lowest CO_2 footprint of the CCS kilns. In both climate-ambitious scenarios, most CCS kilns use the MEA technology. However, MEA CCS kilns require more CCS per kilogram of clinker due to the high thermal

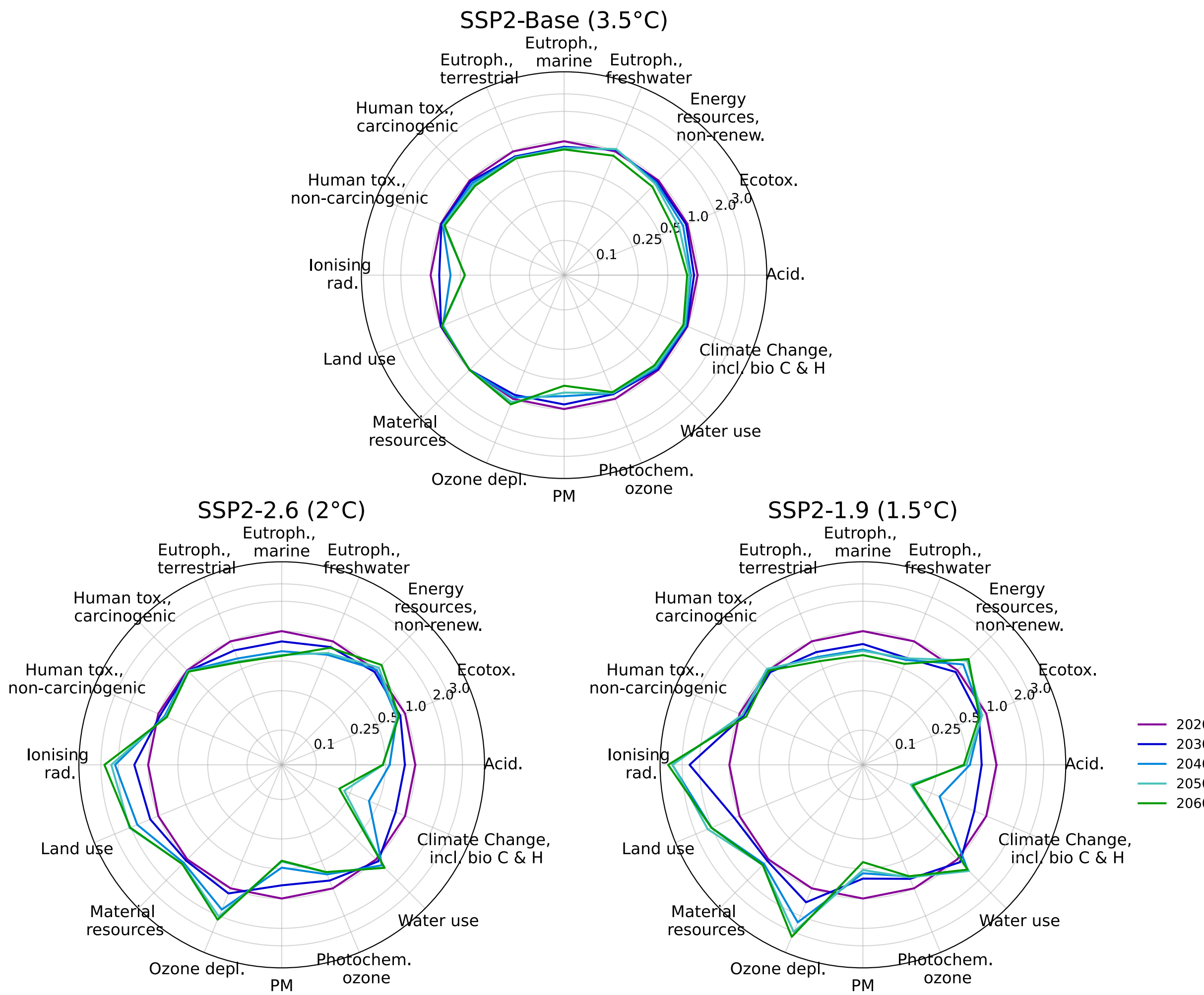

Fig. 8. Results for 1 kg clinker from the world market between 2020 and 2060 in the three scenarios for the 16 impact categories of the EFv3.0 impact assessment method. Scenarios include changes in cement production and the other industrial sectors. All impacts are normalized by the 2020 values (2020 = 1) on a log10 scale. PM = particulate matter. Fig. A9 shows these results relative to the impacts in the baseline scenario of the same year.

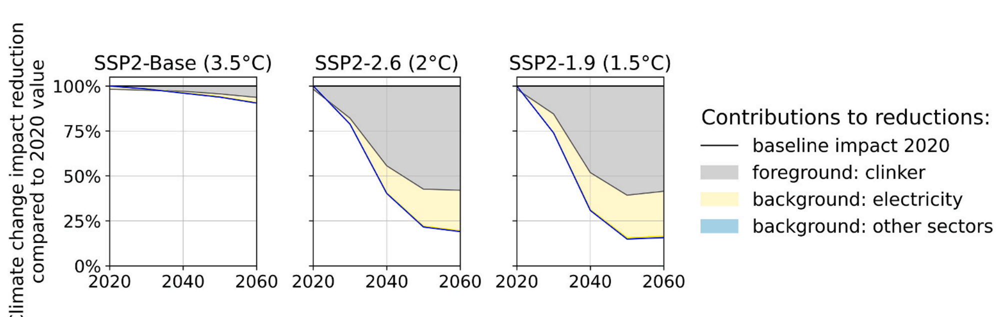

Fig. 9. Reductions in climate change impacts of 1 kg clinker from the world market compared to 2020 impact if foreground scenarios (clinker) and background scenarios (electricity, steel, fuels, transport, non-CO2 emissions, and CCS) are separately or jointly implemented.

energy demand for MEA regeneration and the additional capture of CO_2 from the provision of this heat than the less energy-intensive and more electricity-fed Oxy CCS kiln technology, see Fig. 5. Thus, a lower CCS demand could be achieved by switching to less energy-intensive CCS options with high efficiency, such as Oxy CCS.

4. Discussion

4.1. Data and comparability challenges

PLCA is a data-intensive assessment requiring a high level of detail to assess future environmental impacts accurately. In our application of coupling this to a process-based IAM with a higher granularity on sectoral representations (van Sluisveld et al., 2021), we found there was a distance between data representation used in IAMs and needed detail for pLCA. For example, IMAGE's fuel mixture represents the non-metallic

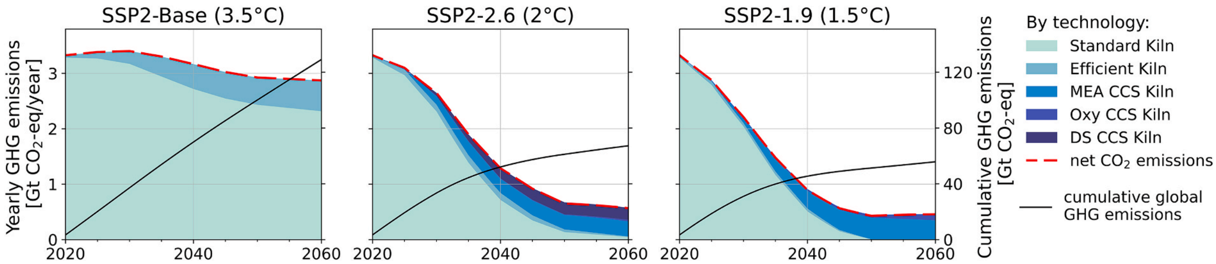

Fig. 10. Yearly and cumulative life cycle GHG emissions of the clinker industry, in SSP2-Base (3.5 °C), SSP2-2.6 (2 °C), and SSP2-1.9 (1.5 °C) scenario in Gt CO_2-eq/year.

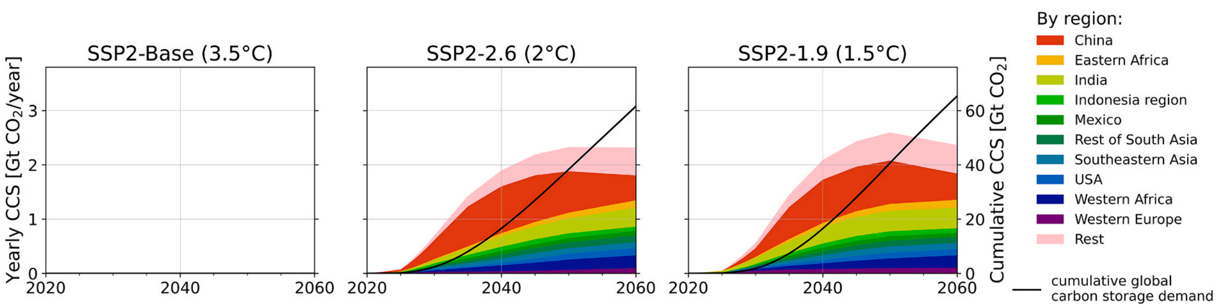

Fig. 11. Projected yearly carbon captured (left axis) and cumulative carbon storage demand (right axis) for clinker production scenarios SSP2-Base, SSP2-2.6, and SSP2-1.9. Absolute values listed in Table A11.

mineral sector and not specifically the cement sector (see 2.2.2). As no data on future fuel composition for cement production on a global level was available, the IMAGE mix was used as a proxy, acknowledging that it does not reflect the specific characteristics of the cement sector (Georgiopoulou and Lyberatos, 2018).

By making the code of this study available (https://doi.org/10.5281/zenodo.10255594), we hope to support future LCA practitioners in creating IAM-compatible database-wide prospective LCA scenarios for other product groups not yet covered or for other IAMs. With a growing number of pLCA studies, topics like transparency, reproducibility, and interoperability will be venues for further development.

Regardless, our climate change impact results for current clinker production (global average 1.03 kg CO2-eq/kg clinker in 2020) are consistent but slightly higher than those reported in the literature (Cao et al., 2021; Favier et al., 2018; GCCA, 2019). These literature values, however, only cover direct emissions and lack a life cycle perspective. Results for clinker produced by CCS kilns are in the same order of magnitude as in the literature (Bacatelo et al., 2023; Cavalett et al., 2022; Georgiades et al., 2023; Leilac, 2021a), yet a direct comparison is difficult due to different assumptions on allocation, system boundaries, fuel mix, regional and temporal scope, and the additional characterization of biogenic CO_2 flows in our study. Leilac (2021a) finds that linking CCS to the emissions from steam generation for MEA reclamation, as implemented in this study, results in an additional reduction of 0.19 kg CO_2/kg clinker. This highlights the importance of a holistic MEA CCS kiln design.

4.2. Importance of an integrated scope in sectoral analysis

Regarding sectoral pathways, this study aligns with the existing literature regarding the baseline pathway for cement production. However, our climate-ambitious scenarios show a greater reliance on (BE)CCS (Dekker et al., 2023) than found in other studies (e.g., Cao et al. (2021); Georgiades et al. (2023)). This suggests (1) an overestimation of the required CCS capacities needed to decarbonize the clinker and cement value chain and (2) a reliance on biobased fueling of clinker kilns.

In regards to the former, while literature generally agrees on the need for large-scale CCS deployment to reduce emissions (Georgiades et al., 2023; Obrist et al., 2021; GCCA, 2021; IEA, 2018; Obrist et al., 2021), no commercial CCS facility is currently operating in the cement sector: only 0.4 Mt CO_2/year capture capacity is under construction, 7.3 Mt CO_2/year under advanced development, and 13 Mt CO_2/year under early development (Global CCS Institute, 2023). Assuming that all announced CCS facilities will be constructed and operated at maximum capacity by 2030 leads to 20.7 Mt CO_2 captured and stored for the cement sector per year in 2030. Even under these optimistic assumptions, this capacity is less than 4% of the required capacity in the climate-ambitious scenarios (SSP2-2.6: 702 Mt, SSP2-1.9: 565 Mt) in 2030. Adopting CCS in the cement industry faces significant challenges such as high investment costs, long kiln lifetimes (Cembureau, 2022), higher production costs of clinker from CCS kilns (Agora Energiewende, 2019; Fleiter et al., 2021), and additional investments in infrastructure for CO_2 transport and storage (Fleiter et al., 2021). These obstacles can lead to a prolonged reliance on existing clinker production technologies, called *carbon-lock-in*, impeding the global cement industry from achieving the necessary emission reductions at a pace sufficient to meet future climate targets. Hence, given the lack of momentum for CCS, some argue that near-future mitigation scenarios should focus more on demand-oriented measures. Decarbonization roadmaps from the Global Cement and Concrete Association (GCCA, 2021), Favier et al. (2018) and Cao et al. (2021) underline the importance of a broader mitigation portfolio, including novel non-clinker-based cement and material efficiency measures in the construction sector. This is also supported by Georgiades et al. (2023), who find a similar impact reduction for cement production at the European scale by 2050 with less application of CCS and higher reduction contributions from clinker substitution, alternative fuels, and improved kiln efficiency. The GCCA also projects a reduction of 242 Mt CO_2-eq/year by mid-century through cement carbonation in their assessment, which is the gradual uptake of CO_2 by cement over time during the use-phase. However, the effect of carbonation is controversial and highly dependent on the structure's geometry and additional cement treatment at the end-of-life stage (Sacchi and Bauer, 2020). Overall, it could be valuable for future work to adopt such broader measures to the sectoral transformation pathway as a whole.

In regard to the latter, carbon-neutral clinker in this study is only achieved when clinker kilns are fueled with biobased energy carriers and upstream electricity generation with a large BECCS share. This combination offsets residual direct emissions from CCS kilns with the credits from CO_2 sequestration during biomass growth. The IMAGE-based model predicts a significant shift from fossil to bio-based fuels in the climate-ambitious scenarios. However, securing these additional resources may be challenging due to competition across sectors, as other industries are also turning to bio-based fuels to lower their climate change impact (Rulli et al., 2016; Yang et al., 2021). Increased biomass demand may lead to land competition and undesired effects like increased food prices or indirect land-use change. Additionally, biofuels increase energy consumption in cement kilns due to lower calorific value and higher heterogeneity (Brunke and Blesl, 2014), which was neglected in this study. Like biomass, many industries also turn to low-carbon electricity as a mitigation lever, and the feasibility of supplying the quantities of low-carbon energy carriers required by all sectors remains uncertain (Carrara et al., 2020). Maintaining a fully integrated perspective is, in this case, essential to deduct the impact of a sectoral transformation pathway fully.

5. Conclusion

This study has presented a prospective life cycle assessment (pLCA) for the global clinker production until 2060 for a 3.5°C-baseline, 2°C- and 1.5°C-compatible scenario, using scenarios from the IMAGE integrated assessment model. A deep futurization of the supply chains in the life cycle inventory database ecoinvent v3.9.1 is achieved by combining scenarios for foreground clinker production with consistent scenarios for other major background sectors.

Our life-cycle-based results show that a net-zero clinker production may not be achieved by 2060 with the production-oriented transition pathways considered in this study. Using pLCA, any greenhouse gas emitted across scopes 1, 2, and 3 is quantified, a significant advantage over other studies that only assess direct CO_2 emissions in clinker production. The pLCA results show a substantial reduction in life cycle climate change impacts for global clinker production by 81% in the 2°C- and 84% in the 1.5°C-compatible scenario compared to production in 2020. Despite this substantial reduction, residual emissions remain primarily from legacy kilns. The cumulative emissions from global clinker production between 2020 and 2060 account for 5% and 11% of the remaining carbon budget until the end of the century in the 2°C- and 1.5°C-compatible scenario, respectively.

The transformation of the global clinker sector depends on wider system changes that mainly negatively affect other categories of environmental impact. A burden shift to other impact categories is observed, such as ionizing radiation, ozone depletion, material resources, and land use. These have resulted from changes in clinker production and the broader economy, e.g., the power supply system. However, the prospective results for other impact categories are less robust, as this framework does not implement future consequences of policies that govern non-climate-related environmental impacts, e.g., the Montreal Protocol. Future research should increase our understanding of prospective changes in impact categories beyond climate change. Feeding this trade-off between different environmental impacts into the IAM into a multi-objective optimization might propose other optimal solution pathways.

Expanding pLCA assessment to adopt a wider set of transition pathways, including a wider basket of mitigation levers, is considered the next venue for development. In this study, we have presented the coupling of a pLCA framework to the IMAGE integrated assessment model, which allowed us to study production-focused transition pathways with limited demand-side responses. As a result, this study projected higher CCS deployment for clinker production than what is foreseen in other roadmaps and significantly surpasses the announced plans of the cement industry. As demand-side mitigation options could significantly affect the mitigation strategy and the life cycle impacts across the value chain, it warrants complementing the production-oriented transition pathways with other promising mitigation options for the clinker and cement sector. These could be additional production-oriented technologies, such as electric kilns and hydrogen kilns, alternative binders, supplementary cementitious materials, and cement carbonation, or demand-focused mitigation options, such as material reduction, substitution, and reuse. Although such analysis would come with data and representational challenges in the applied modeling frameworks, it may offer a more balanced view on how to avoid lock-ins in the carbon-emitting clinker and cement value chain with a lower reliance on CCS.

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CRediT authorship contribution statement

Amelie Müller: Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Carina Harpprecht:** Writing – review & editing, Supervision, Software, Methodology, Conceptualization. **Romain Sacchi:** Writing – review & editing, Software. **Ben Maes:** Writing – review & editing, Data curation. **Mariësse van Sluisveld:** Writing – review & editing, Data curation. **Vassilis Daioglou:** Writing – review & editing, Data curation. **Branko Šavija:** Writing – review & editing, Supervision. **Bernhard Steubing:** Writing – review & editing, Supervision.

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.

Data availability

All data and code is shared in the Zenodo repository https://zenodo.org/records/10255594.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.141884.

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