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Prospective life cycle assessment of European cement production

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ABSTRACT

Various measures can be employed to decarbonise cement production, including clinker substitution, alternative fuels, kiln improvements, and carbon capture and storage. In this study, we quantify the CO_2-eq. emissions mitigation potentials of these measures on typical cement production in Europe until 2050 using prospective life cycle assessment, including the influence of possible futures of socioeconomic development. We combined environmental product declaration data for cement production with a modified life cycle inventory database (based on ecoinvent v.3.6) that incorporates scenarios developed using the IMAGE (Integrated Model to Assess the Global Environment) integrated assessment model (IAM). The IAM translates socio-economic factors into environmental data that follow Shared Socioeconomic Pathways (e.g., SSP2) to consistently describe possible futures of socio-economic development and environmental change beyond cement production, i.e., the 'background effects'. The results show that in 2050, cement can be produced with significant CO_2-eq. emissions reductions using clinker substitution (42%), alternative fuels (25%), or improved kiln efficiency (12%) relative to 2020. When combined, these measures could reduce CO_2-eq. emissions of cement production by ~58% (excluding carbon capture and storage) and ~88% (including carbon capture and storage) by 2050 relative to year 2020, which could lower CO_2-eq. emissions to as low as 0.09 kg per kg cement by 2050. The effect of using future decarbonisation scenarios for the electricity mix on the results is an additional ~10% reduction in CO_2 -eq. emissions by 2050. Multiple credible pathways exist for the cement sector to achieve and surpass CO_2-eq. emissions reductions consistent with global climate targets.

1. Introduction

Cement production generates ~7–8% of global anthropogenic CO_2 emissions (Mikulčić et al., 2016)[1]. Portland cement (PC) is by far the dominant cement type produced and is formed by heating limestone and clay to ~1450 °C (IEA, 2018). The sintered clinker product is then ground and mixed with other minerals such as gypsum, limestone, blast furnace slag, and coal fly ash (GCCA, 2022). Cradle-to-gate CO_2 emissions from PC clinker production are approximately 798 kg (world average) and 712 kg (European average) per t clinker, which mainly arise from reactions of the raw materials (i.e., process-based) and fossil fuel combustion (i.e., energy-based) (GNR, 2019a, 2019d) Emissions from PC production depend on several factors, including the amount of clinker produced, plant location, kiln fuel, electricity mix, as well as production efficiency (Petek Gursel et al., 2014).

In line with the Paris Agreement, the International Energy Agency (IEA) has set a 24% CO_2 emission reduction target (compared to pre-industrial levels) from cement production to contribute to limiting the global mean temperature rise to 2 °C by year 2100 (IEA, 2018). The European Commission's 'Green Deal' proposes a more ambitious goal for Europe to become carbon neutral by 2050, which requires limiting global temperature rise to 1.5 °C by 2100 (Cembureau, 2020). To meet these climate targets, the cement industry needs to reduce CO_2 emissions at a significantly faster pace than the historic trend between 2005 and 2018 (~0.4% reduction per year in kg CO_2 per t clinker). It is important to quantify the potential of current decarbonisation measures to reduce CO_2 emissions by 2050 and meet the climate targets.

To quantify the decarbonisation potentials of such measures in terms of CO_2-eq. emissions, life cycle assessment (LCA) is used. Traditionally, LCA is applied as a one-off diagnostic tool to determine the

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[1] We purposely distinguish between CO_2 and CO_2-eq. emissions, with the former term referring to CO_2 emissions only, and the latter including other climate change pressures.

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environmental performance of an established or existing technology (Cucurachi et al., 2018). This traditional LCA approach has been applied to assess the life cycle environmental performance of conventional cement production and alternate (including less CO_2 emitting) technologies. Typical measures that have been studied by LCA to reduce CO_2-eq. emissions from cement production are to replace clinker with supplementary cementitious materials (SCMs, such as coal fly ash and blast furnace slag), switching to alternative fuels for combustion (e.g., reducing petroleum coke and hard coal used as the primary kiln fuels with e.g., refuse-derived fuel, RDF), improving kiln configurations to achieve higher production efficiencies (e.g. reducing heat losses) and carbon capture and storage (CCS) (Mikulčić et al., 2016).

Many LCA studies have investigated the climate change impact caused by clinker replacement with SCMs such as blast furnace slag, coal fly ash, metakaolin, limestone, rice husk ash, and volcanic ash. These studies have shown that composite PC containing such SCMs can have significantly reduced CO_2-eq. emissions footprints (reductions of 15–88% at clinker-to-cement ratios of 0.85–0.1) relative to ordinary PC (Miller et al., 2018; Rahla et al., 2019; Arrigoni et al., 2020). The major CO_2-eq. emissions reduction effect is due to reducing PC clinker content, which decreases CO_2 emissions from both calcination and fuel consumption.

The use of alternative fuels in cement kilns is reported to have a potential to reduce CO_2 emissions from cement production by 20–30% [including refuse- and tire-derived fuels (Georgiopoulou and Lyberatos, 2018; Dziok et al., 2021), sewage sludge ((Husillos Rodríguez et al., 2013; Dziok et al., 2021)), non-recycled plastics and paper (Thanos) Bourtsalas et al., 2018), and natural gas (Thwe et al., 2021)]. Incorporating waste fuels in the mix (e.g., waste tires, agricultural waste, solid waste, and oil waste) utilises otherwise lost energy (from fuels being landfilled) and reduces CO_2-eq. emissions associated with fossil fuel mining, transportation, and combustion (Mokrzycki et al., 2003; ICF International, 2008).

Energy use in cement production can be reduced in a variety of ways, leading to CO_2 emissions reductions. Pyro-processing heat losses can be as much as 20% of energy inputs and cause 8% CO_2 emissions of cement production (Engin and Ari, 2005), heat integration can provide up to 35% of cement plant thermal energy requirements (Khurana et al., 2002), and using higher thermal efficiency kiln configurations such as shifting from a wet process to a dry process with a precalciner, irrespective of the state of the cement plant (new or retrofitted), can reduce energy use by 50% and CO_2 emissions by 20% (IEA, 2018, 2021). The extent of CO_2 emissions reduction depends highly on the changes in process equipment and changing the cement kiln configuration has a reported potential to reduce CO_2 emissions by 15–20%.

Carbon capture and storage (CCS) is versatile technology that is applicable in various industries (iron and steel, cement, petrochemicals, etc.) (Kuramochi et al., 2012). CCS aims to capture process-based CO_2 emissions prior or after fuel combustion (pre- and post- combustion technologies, respectively). Calcium looping is a type of CCS technology in which the CO_2 in the flue gas is removed using a calcium oxide sorbent to form a high purity, concentrated CO_2 stream. (Tilak and El-Halwagi, 2018; Colelli et al., 2022. LCA studies investigating CCS technologies such as oxy-fuel and post-combustion (i.e., amine scrubbing) show a wide range of CO_2-eq. emissions reduction potentials (15–78%) that are affected by several parameters (i.e., CO_2 capture technology, CO_2 capture efficiency energy consumption, and energy source) (Volkart et al., 2013; D. García-Gusano et al., 2015; Hills et al., 2016; Miller et al., 2018). These parameters include capture efficiency (e.g., 85%), technology type (e.g., post-combustion), and fuel source (e.g., natural gas) (An et al., 2019; Chen and Yang, 2021; Wunderlich et al., 2021). Importantly, CCS has only been tested in pilot and demonstration plant scales (International Association of Oil and Gas producers, 2022) i.e., in the Norcem cement plant in Brevik, Norway (Bjerge and Brevik, 2014) and in the HeidelbergCement plant in Lixhe, Belgium (LEILAC 2, 2021), where the energy source powering the process was highlighted as a key parameter affecting the CO_2 emissions mitigation potential. The follow-on project in HeidelbergCement aims to accelerate the implementation of CCS at the commercial scale, by testing the performance of a demonstration plant to capture 20% of the CO_2 emissions from a conventional cement plant (LEILAC 2, 2021). Other recent projects involving CCS include e.g., Cleankerk in Buzzi Unicem cement plant in Vernasca, Italy (Fantini et al., 2020), Lighthouse Carboneras in the LafargeHolcim cement plant in Almeria, Spain (Carbon Clean, 2020), Carbon2Business in the LafargeHolcim Lägerdorf cement plant in Germany (Holcim, 2020), ANRAV in the HeidelbergCement Devnya cement plant in Bulgaria (HeidelbergCement, 2022), and a full-scale CCS system by HeidelbergCement and Cementa in the Slite cement plant in Sweden, which has a target to capture the plant's total process CO_2 emissions (1.8 Mt CO_2 per year) by 2030 (CO_2-eq. emissions arising from other life cycle stages are not included in this target) (HeidelbergCement, 2021).

LCA studies that aim to assess the environmental performance of product systems in the future, which is important for emerging technologies on which decarbonisation measures are based, should use a prospective LCA approach. Prospective LCA accounts for upscaling of emerging technologies to industrial application and or an existing technology to a future state where changes may have occurred on both the specific technology under study (i.e., in this study we focus on existing PC production) as well as the wider technological surroundings (i.e., electricity mix). If these changes are not captured, the reliability of the results may be compromised (Miller and Keoleian, 2015; Villares et al., 2017) and limit their application to analyse future scenarios. The main challenge in a prospective LCA study, however, is dealing with the epistemological uncertainty (due to lack of case specific data) which is inherent in future models (Joyce and Björklund, 2019). To overcome this uncertainty, it has been suggested to use future scenarios that describe plausible future states of the product system(s) under analysis (Pesonen et al., 2000; Spielmann et al., 2005; Villares et al., 2017; Mendoza Beltran et al., 2020). Future scenarios should be developed based on direct (foreground) and indirect (background) system parameters for case studies where indirect parameters are deemed important. Examples of the system parameters considered in this study are the kiln type (foreground) and electricity mix (background).

Few studies have assessed future life cycle environmental impacts of cement production in combination with multiple decarbonisation measures and the prospective LCA approach. Amongst the relevant studies published, Yao et al. (2020) assessed the environmental performance of a 3D printed geopolymer concrete panel compared to a conventional PC concrete panel. Maes et al. (2021) studied an emerging electro-mass separation technology to separate fly ash into several fractions and use the resulting product as a substitute for silica fume in ultra-high-performance concrete. This electro-mass separation technology was environmentally assessed at pilot and industrial scale to evaluate the environmental benefits of separating fly ash prior to its use. The future environmental assessment considered background changes by investigating the influence of changes to the electricity mix, based on projections from the European Commission on energy, transport and greenhouse gas (GHG) emissions. The influence of electricity mix (background changes) and scale-up drastically reduced the life cycle CO_2 emissions of the emerging electro-mass separation technology (~ –4,000 kg CO_2 eq.) compared to the incumbent (~ –1,000 kg CO_2 eq.) method (direct use of Class F coal fly ash in cement). Prospective LCA has not yet been used to investigate the influence of direct (foreground) and indirect (background) system parameters on the CO_2-eq. emissions of cement production.

In this work, we apply prospective LCA to comprehensively investigate the climate change impacts of decarbonization measures for cement production, including the influence of both foreground and background (decarbonisation in electricity production) system parameters. Modelling the effects that decarbonising electricity generation has on the CO_2-eq. emissions footprint of cement production, including with kiln electrification, is important given the growing interest in this topic (Ellis et al., 2020; GCCA, 2021). We focus on European cement production and greenhouse gas emissions induced climate change impacts until the year 2050. To do this, we develop six foreground scenarios to assess important cement related developments (i.e., clinker substitution, alternative fuels, kiln improvements, and carbon capture and storage), but also include prospective life cycle inventory background scenarios (i.e., electricity mix) that indirectly affect cement production, and that have been developed based on broad and global storylines of socio-economic pathways (SSPs, i.e., SSP2).

2. Methodology

2.1. Goal and scope

The goal of this study is to investigate the potential changes in greenhouse gas emissions induced climate change impacts (in terms of CO_2-eq. emissions over a 100-year horizon) from incorporating decarbonisation measures into cement production until 2050. These interventions include: (i) PC clinker substitution with SCMs, (ii) increased use of alternative fuels in cement production, (iii) improvements in kiln efficiency, and (iv) implementing CCS. For (i) PC clinker substitution

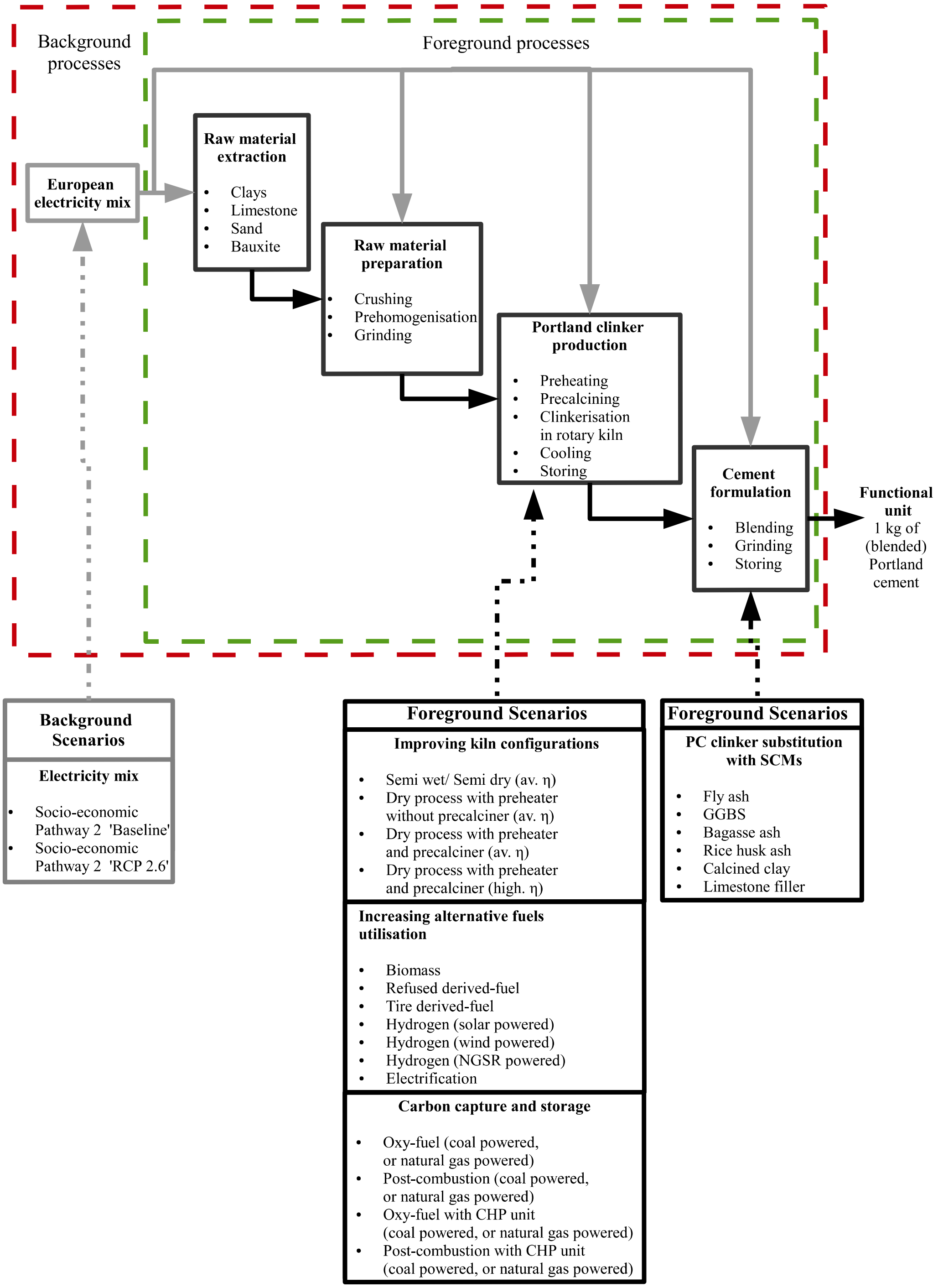

Fig. 1. System boundary of this prospective LCA study, including foreground changes on (i) SCMs, (ii) alternative fuels, (iii) kiln configurations with higher efficiency (η) and (iv) CCS. Background changes are included based on the SSP2 pathways (Baseline and RCP 2.6, see Section 2.3).

with SCMs, evaluation was performed solely on the influence of the SCM upstream/pre-treatment processing on the climate change impact and no physical properties (e.g., compressive strength) were considered. The functional unit is 1 kg cement produced at the factory gate (Fig. 1). This study only considers the climate change impact category and additional research is needed to evaluate potential impacts in other impact categories (see Supplementary Information S1 for further details).

A functional unit incorporating physical properties (i.e., compressive strength) in terms of 1 kg binder per m^3 MPa concrete, as defined by Damineli et al. (2010) as the binder intensity, could result in a closer comparison between the various blended cement types studied. This addition to the functional unit enables blended cement to be assessed in terms of both mechanical and environmental performance. However, depending on the strength class desired and type of SCM used, the clinker-to-cement ratio can vary significantly. This makes it difficult to analyse the effect of changing the clinker-to-cement ratio on the CO_2-eq. emissions footprint of cement. In this paper we focus on analysing this effect of changing the clinker-to-cement ratio using relatively simple single SCM systems, leaving comparisons of more complex composite PCs for future work. We do this noting that composite PCs can have both relatively low clinker-to-cement ratios and comparable or faster compressive strength development than ordinary PC, e.g., limestone calcined clay cement (clinker-to-cement ratio = 0.5) (Maraghechi et al., 2018).

We use a cradle-to-gate system boundary that includes raw material extraction, raw material preparation, clinker production, cement formulation, and transportation amongst the foreground activities. We choose Europe as our geographical scope due to the high availability of data for this region. This enables our study to become a reliable reference point for future prospective LCA studies of cement production in other regions including globally. This choice of scope does not capture more local conditions, e.g., governmental regulations, electricity mix, market size, raw material availability and logistics in each cement plant, which makes this study generic rather than specific to individual production sites.

We analyse climate change impacts based on the 100-year global warming potential (GWP), using the IPCC 2013 method (Tun et al., 2020). The IPCC 2013 method was the most current version available in the software that was used. Activity Browser software (version 2.6.3) and its implementation of the superstructure approach was used to carry out this prospective LCA study (Steubing et al., 2020; Steubing and de Koning, 2021).

Results from the existing literature are used in a non-harmonized manner to compare to the results of this study, meaning that they do not use the same methodological choices. For example, some studies use the IPCC impact assessment method (e.g., Arrigoni et al., 2020; Miller et al., 2018), whereas others use CML 2001 (i.e., Rahla et al., 2019).

2.2. Foreground scenarios

The foreground system describes PC production and comprises four steps: (1) raw material extraction, (2) raw material preparation, (3) clinker production, and (4) cement formulation (Fig. 1). The raw materials for clinker production are limestone and a range of materials in smaller quantities including clays, sand, bottom ashes, and bauxite to make up the required feedstock composition. The primary raw materials are quarried and then transported to the cement plant, where they are crushed, milled, and/or mixed to form a homogenous fine powder. Depending on the kiln configuration, the fine powder is processed through a series of heat exchangers, heating the material up to ~900 °C during which limestone is decomposed to lime, releasing CO_2 emissions. This calcined material is then fired in a kiln to high temperatures (~1450 °C) to produce PC clinker. The produced PC clinker exits the kiln and is rapidly cooled before being further processed into cement, which is typically performed by milling and mixing the material with ~5 mass% gypsum (and sometimes additional materials e.g., limestone, quicklime depending on the final cement properties) to form ordinary PC (IEA, 2018). In Europe, ordinary PC is standardised as CEM I (ISO EN 197–1, 2011). Secondary raw materials such as blast furnace slag, coal fly ash, limestone can be blended to replace a fraction of clinker in the produced cement.

We develop six (1–3, 'individual'; 4–6, 'synergistic') foreground scenarios for CEM I production that correspond to the implementation of decarbonisation measures. Both individual and synergistic scenarios were developed using both International Energy Agency (IEA) and European Cement Association (CEMBUREAU) roadmaps (IEA, 2018; Cembureau, 2020). The parameters and their values that are used in these scenarios are shown in Supplementary Information S1. The scenarios are:

1 PC clinker substitution with SCMs (Section 2.2.1)
2 Increasing alternative fuels utilisation (Section 2.2.2)
3 Improving kiln configurations (Section 2.2.3)
4 Effect of allocation type: synergistic scenario incorporating all three of these individual decarbonisation measures, based on IEA and CEMBUREAU roadmaps investigating the influence of the allocation approach taken, to allocate the upstream impacts in cases of by-product production (none, and economic) (Section 2.2.4)
5 Effect of technology roadmap: synergistic scenarios incorporating all three of these individual decarbonisation measures, based on IEA and CEMBUREAU roadmaps compared to GCCA roadmap (Section 2.2.4)
6 Effect of carbon capture and storage: synergistic scenario incorporating all three of these individual decarbonisation measures, based on IEA and CEMBUREAU roadmaps, and additionally CCS (Section 2.2.4).

These six scenarios were developed according to projections in International Energy Agency (IEA) and European Cement Association (CEMBUREAU) roadmaps (IEA, 2018; Cembureau, 2020), specifically following changes in the clinker-to-cement ratio, alternative fuels in the kiln fuel mix, and kiln efficiency improvements to 2050. The IEA cement roadmap presents a realistic transition pathway for cement production to achieve a 24% reduction of direct CO_2 emissions by 2050, which is consistent with the Paris Agreement target of limiting the global temperature rise to less than 2 °C above pre-industrial levels (1980) (UNFCCC, 2015). The CEMBUREAU roadmap promotes a more ambitious pathway for the European cement industry targeting the objectives of the Green Deal to contribute to limiting the global temperature rise to 1.5 °C by 2050, with a 63% direct CO_2 emissions reduction for cement production by 2050. The influence of the technology roadmap on climate change impact was determined through a fifth synergistic scenario (i.e., incorporating PC clinker substitution, alternative fuels, and improved kiln configurations), which was developed according to the GCCA roadmap, to compare against the IEA and CEMBUREAU roadmaps. The GCCA roadmap sets out a pathway to achieve a net zero CO_2 emissions cement production by 2050, with an intermediate target of 25% CO_2 emissions reduction by 2030 (Cembureau, 2020). Similarly, to the CEMBUREAU roadmap, the GCCA roadmap (GCCA, 2021) is based on limiting the global mean surface temperature rise to 1.5 $^{\circ C}$ above pre-industrial levels. These roadmaps use the same decarbonisation measures (PC substitution with SCMs, improving kiln type configurations, and implementing CCS). A sixth synergistic foreground scenario was developed based on the IEA and CEMBUREAU roadmaps that includes CCS in addition to the other individual decarbonisation measures (clinker substitution, alternative fuels, improved kiln configurations).

The inventory analysis input data for CEM I production were extracted from the environmental product declaration tool by the Global Cement and Concrete Association (GCCA) (WBCSD, 2016), which is based on data from the Getting the Numbers Right (GNR) database (Dauriat et al., 2019). The scope of the GCCA environmental product declaration tool data includes raw material extraction and preparation, transportation, clinker production, and cement formulation. Input data associated with pre-treatment of SCMs, and alternative fuels production were extracted from the existing literature [ground granulated blast furnace slag, coal fly ash (Gursel, 2014), rice husk ash, bagasse ash (Jittin et al., 2021), calcined clay (Salvi Malacarne et al., 2021), hydrogen production (Dufour et al., 2011; Cetinkaya et al., 2012), sewage sludge (Dufour et al., 2011), tire-derived fuel (Gursel, 2014), refused-derived fuel (Grzesik and Malinowski, 2016), and biomass (Sgarbossa et al., 2020).

2.2.1. PC clinker substitution with supplementary cementitious materials

The PC clinker substitution with SCMs foreground scenario models substituting PC clinker with primary and secondary cementitious materials such as industrial and agricultural by-products. We assume that the PC clinker substitution rate increases linearly from 20% in 2020 (WBCSD, 2016) to 30% in 2030, 40% in 2040, and 50% in 2050. Currently, the most dominant SCMs are limestone, coal fly ash, blast furnace slag, and silica fume (Juenger et al., 2012). Other SCMs that are receiving relatively high attention include rice husk ash, bagasse ash, and calcined clay. We include the following SCMs in binary PC-SCM composite cements and treatment processes in our foreground system boundary:

- Class F coal fly ash, which is produced in power plants during coal combustion and undergoes drying prior to transport to cement plants (Chen et al., 2010; Gursel, 2014). Both drying and transportation are included here. To investigate the effect of emissions allocation (economic compared to no allocation) on our LCA results we included upstream process emissions from primary production, i.e., electricity production at coal power plants. Allocation was only performed for the case of coal fly ash.
- Blast furnace slag, which is produced during iron production in blast furnaces. The slag is treated through quenching and granulation, dewatering and/or drying, grinding, storage, and is then transported from iron to cement plants (CTL, 2003; Petek Gursel et al., 2014). Quenching, dewatering, crushing, grinding, storage, and transportation were included in the inventory.
- Bagasse ash, which is generated via combustion of bagasse residue from sugar production. Bagasse ash can be ground and then transported to cement plants to be used as an SCM (Jittin et al., 2021). Both grinding and transportation are included here.
- Rice husk ash is produced via combustion of rice husks, which is a by-product from rice production. Rice husk ash is typically dried and then transported to cement plants (Jittin et al., 2021). Both drying and transportation are included here.
- Calcined clay is produced by heating kaolinite-rich clay to between 650 °C and 750 °C. Its production includes kaolinite extraction, production, calcination, and transportation to the cement plant (Salvi Malacarne et al., 2021). Raw material extraction and processing, and transportation are accounted for.
- Fine limestone is produced by extracting limestone rock, then crushing and finely grinding the material (Rebello et al., 2019).

Although coal fly ash and blast furnace slag are currently highly used SCMs, their future supplies are expected to decrease consistent with reduced operation of coal-fired electricity power stations and blast furnaces. Use of other SCMs like calcined clay and ground limestone is expected to increase. Use of alternative SCMs such as rice husk ash may also increase, e.g., due to relatively high local supply (IEA, 2018; GCCA, 2021). A range of such SCMs are modelled here.

The individual influence of the above SCMs to substitute PC clinker on the climate change impact of cement production (i.e., binary SCM-PC systems) using consistent substitution (i.e., 15%, 25%, 35%, 45% for 2020, 2030, 2040, 2050 respectively) ratios for all SCMs is studied. The 2020 results present a theoretical value of what would have been the results with these scenarios, while 2030–2040–2050 data present potential future states.

2.2.2. Increasing alternative fuels utilisation

The alternative fuels foreground scenario models increased utilisation of alternative fuels in cement kilns. In 2020, alternative fuels provided 45% (of which 16% was from biomass e.g., wood pellets and agricultural waste) of the thermal energy requirements in cement kilns, with the remaining 55% covered by fossil fuels. This scenario models an increase in alternative fuel use to 60% (including 30% biomass) by 2030, 75% (including 40% biomass) by 2040, and 90% (including 50% biomass) by 2050. Petroleum coke and hard coal were the fossil fuels replaced by alternative fuels including in a separate, complete electrification scenario variant. We include the following alternative fuels and treatment processes in our foreground system boundary (detailed fuel mix designs are provided in Supplementary Information S1, Section S2.2):

- Biomass is organic matter that can be used as fuel for combustion. We use wood pellets produced from sawdust as the feedstock to represent biomass, since this is the most used feedstock in Europe. Forest operations, transportation, processing units such as milling, drying, pelletising, packaging, and distribution are all included (Sgarbossa et al., 2020).
- Refuse-derived fuel (RDF) is generated from several waste types. Here, we use RDF produced from mechanical-biological treatment of municipal solid waste, including collection and transportation of municipal solid waste, separation, shredding, and bio-drying, as well as final product loading and transport (Grzesik and Malinowski, 2016).
- Tire-derived fuel (TDF) is shredded scrap tires. Even though both whole and shredded tires can be burnt in cement plants, we include both tire transportation and shredding here (Petek Gursel et al., 2014).

Hydrogen can be produced from a variety of feedstocks. We consider two main production routes here. The first and most common route is natural gas steam reforming, in which methane from natural gas is steam heated (usually with a catalyst), to generate a hydrogen-carbon monoxide mixture (syngas). Carbon monoxide is reacted further with steam (in a water-gas shift reaction with a catalyst) to produce carbon dioxide and additional hydrogen. A purified hydrogen stream can then be produced by removing carbon dioxide and any other impurities. For natural gas steam reforming, the processes included in the inventory are raw material extraction, steam reforming plant construction and operation, distribution of electricity and natural gas, and landfilling (Cetinkaya et al., 2012). The second production route that we consider is hydrogen generation via water electrolysis powered by either wind or solar energy. Water electrolysis is a method of hydrogen production in which direct current is passed through an electrolyser to decompose water into oxygen and hydrogen gas (Rajeshwar et al., 2008). In wind-powered electrolysis, electricity would be provided from a wind turbine, and in solar-powered electrolysis, electricity is generated through photovoltaic panels. For wind-powered electrolysis, the processes included are the manufacturing and operation of the wind-turbines, water-electrolysis operation for hydrogen production, and hydrogen storage and compression. For solar-powered electrolysis, the processes included are raw materials and manufacturing of photovoltaic panels, transportation and installation, operation and maintenance, water-electrolysis operation for hydrogen production, and hydrogen storage and compression (Dufour et al., 2011; Cetinkaya et al., 2012). The electrification of the kiln was modelled according to the European electricity mix (mainly electricity sources i.e., Denmark (15%), France (15%), Great Britain (9%), Italy (9%), Spain (7%)).

2.2.3. Improving kiln configurations

The kiln efficiency scenario describes the use of different kiln types regardless of the original cement plant state (new or retrofitted). The average European cement production in 2020 is represented by the semi-wet/semi-dry kiln process with a thermal demand of 3.87 MJ per kg PC clinker. A dry kiln with preheater and without pre-calciner was selected for 2030 (3.68 MJ per kg PC clinker) while the average thermal efficiency for the dry kiln with preheater and pre-calciner was used for 2040 (3.39 MJ per kg clinker). The highest kiln efficiency, which is obtained using a dry kiln with preheater and pre-calciner, was used for 2050 (3.02 MJ per kg clinker). The modelling of changes in kiln configuration includes changes in energy demand and the requirements to construct the kiln in a new cement plant.

2.2.4. Synergistic scenario

The three individual scenarios (Sections 2.2.1-2.2.3) address different parts of the PC production process, and the decarbonisation technologies can be combined to further reduce CO_2-eq. emissions. Therefore, we developed synergetic scenarios incorporating all three decarbonisation measures, without and additionally with CCS. Due to the numerous ways that the decarbonisation measures can be implemented (e.g., use of different SCMs and alternative fuels), we investigated three synergistic scenarios to investigate (a) the maximum potential CO_2 emissions reduction without CCS, (b) the effect of roadmap selection, and (c) the influence of CCS:

a Synergistic scenario without CCS, consistent with the IEA and CEMBUREAU roadmaps, to determine the largest CO_2-eq. emissions per kg cement reduction potential (in 2050) without CCS. This scenario contains 90% alternative fuel use including 20% hydrogen from wind-powered electricity generation and 45% biomass (the remaining 25% is covered by 20% waste plastic, 3% waste solvent, 1% sawdust, and 1% waste oils), a dry kiln type with preheater and precalciner (3.02 MJ per kg clinker) and uses SCMs at a constant clinker-to-cement mass ratio of 0.5.

b Synergistic scenario without CCS, following the GCCA roadmap, to analyse the effect of roadmap selection on modelled CO_2 emissions (in 2050). This scenario contains 90% alternative fuel use (40% natural gas, 35% biomass, 7.5% hydrogen (wind-powered electrolysis) and 7.5% electrification; the remaining 10% consists of oil products and non-renewable waste, i.e., no coal), a dry kiln with preheater and pre-calciner (3.02 MJ per kg clinker), and 50% PC clinker substitution using SCMs. The key difference between synergistic scenarios 1 and 2 and thus the IEA/CEMBUREAU and GCCA roadmaps is the relative share of alternative fuels in the fuel mix (e.g., biomass is 45% in scenario a, and 35% in scenario b).

c Synergistic scenario with CCS, with 90% alternative fuel use (45% biomass; 20% hydrogen; 20% waste plastic, 3% waste solvent, 1% sawdust, and 1% waste oils are used to satisfy the thermal energy requirement), a dry kiln process including a pre-calciner and preheater (3.02 GJ per t of clinker), fly ash as an SCM (50% PC clinker, 45% fly ash and 5% gypsum), and CCS (oxyfuel combustion and separately amine scrubbing, with and without a combined heat and power unit) implemented in 2050. This year of industrial scale implementation was chosen since CCS is currently only implemented at pilot scale.

In the third synergistic scenario (with CCS, synergistic scenario c), the amine scrubbing CO_2 capture unit was modelled with monoethanolamine (chemical absorbent) with an 85% capture efficiency. The same CO_2 capture efficiency (85%) was assumed for the oxyfuel combustion process, and here an air separation unit was additionally included. Both technologies were modelled according to Chen and Yang (2021). These CCS technologies were modelled to be implemented without and with a combined heat and power unit, modelled according to An et al. (2019), to satisfy their thermal demands. Two energy sources – hard coal and natural gas – were compared for both amine scrubbing and oxyfuel processes.

2.3. Background scenarios

When performing prospective LCA, it is important to ensure temporal consistency between foreground and background systems (Arvidsson and Molander, 2017). Here, we relied on prospective life cycle inventory (pLCI) databases that were generated based on an integration of the ecoinvent database (Wernet et al., 2016) and data from the integrated assessment model IMAGE (Stehfest et al., 2014). The integration process is described in detail in (Mendoza Beltran et al., 2020), although here we used a more recent version of the ecoinvent database (v3.6, cut-off system model).

The pLCI databases used are based on shared socioeconomic pathways (SSPs) that describe broad future scenarios for technological and socio-economic change (O'Neill et al., 2014). There are five distinct SSPs, namely "sustainability" (SSP1), "middle of the road" (SSP2), "regional rivalry" (SSP3), "inequality" (SSP4), and "fossil-fuelled development" (SSP5). Each SSP contains narratives for key factors that affect demographics, human development, economy and lifestyle, policies and institutions, technology, and environment and natural resources (see also O'Neill et al., 2017a) . Previous studies have used the five socioeconomic narratives to develop 'baseline' climate scenarios for SSPs1–5 (meaning that they are absent of climate change mitigation policies) (van Ruijven et al., 2014; van Vuuren and Carter, 2014; Riahi et al., 2017; van Vuuren et al., 2017; Bauer et al., 2017). For example, the SSP2 baseline scenario is associated with a global mean surface temperature rise of 3.8–4.2 °C by the end of the century relative to pre-industrial levels (1980). These studies also developed additional scenarios based on representative concentration pathways (RCPs), which describe climate change mitigation policies and technological change to limit radiative forcing to 6.0 (RCP 6.0), 4.5 (RCP 4.5), 3.4 (RCP 3.4), 2.6 (RCP 2.6), and 1.9 (RCP 1.9) W per m^2 by 2100 (van Ruijven et al., 2014; Van Ruijven et al., 2014; Riahi et al., 2017; van Vuuren et al., 2017; Schandl et al., 2020). The RCP 2.6 scenario limits the global mean surface temperature change rise to 2 °C relative to pre-industrial levels (O'Neill et al., 2014).

Both the SSPs and RCPs have been used by integrated assessment models (IAMs) to generate quantitative future scenarios to assess, amongst others, climate change impacts across economic sectors, regions, and time, typically until 2100. The IMAGE model (Stehfest et al., 2014) consists of a group of integrated models, including energy, agriculture, land, ocean, and atmosphere models. Its energy model (TIMER) is able to provide, amongst others, regionally disaggregated market shares for energy technologies and efficiency improvements over time. Data from IMAGE was used by Mendoza et al. (2020), relying on the Python-based 'wurst' framework (Mutel, 2022), to transform the ecoinvent database to represent future time steps and scenarios. These transformations were limited to the electricity sector in Mendoza Beltran et al. (2020), with the other sectors in the resulting pLCI databases based entirely on the ecoinvent database. Thus, the background system in our study only accounts for the influence of future changes in electricity generation on the climate change impacts of cement production. Data for two scenarios, the SSP2 baseline (3.8–4.2 °C warming by 2100 relative to 1980) and SSP2 RCP 2.6 (~2 °C warming by 2100 relative to 1980) were available.

Four-time steps were accounted for (2020, 2030, 2040, and 2050), which resulted in a total of 8 pLCI databases (four for each scenario). In order to facilitate the practical modelling, we applied the superstructure approach that merges the individual pLCI databases into a single 'superstructure' LCI database and an associated 'scenario difference file' (Steubing and de Koning, 2021). The superstructure database contains all processes, intermediate and environmental flows that are present across all individual prospective LCI databases, while the scenario difference file contains existing differences in the flow values for all time steps and scenarios selected. The superstructure database can be converted into any of the original pLCI databases with the data contained in the scenario difference file. This enables the LCA practitioner to use a single background database (the superstructure database) instead of multiple ones to represent all scenarios and time steps. The scenario difference file was also simultaneously used to accommodate foreground (e.g., cement production) and background (e.g., electricity generation) scenario data (Fig. 1). We used the open source LCA software Activity Browser and implemented the superstructure modelling approach with a modified ecoinvent database (v3.6, cut-off system model) (Steubing et al., 2020).

2.4. Uncertainty analysis

The quantitative uncertainty of our results was investigated using Monte Carlo analysis. We focused on the influence of PC clinker because it is the key contributor to cement production CO_2-eq. emissions. The mass of PC clinker used in cement formulations was classified using data quality indicators in a pedigree matrix based on a scoring system (scale 1–5), which assesses judgements on data integrity, reliability, temporal correlation, geographical, and technological uncertainty (Weidema et al., 2013). These indicator scores were used to generate probability density functions (PDFs) using log-normal distribution (Yu et al., 2018). PDFs were generated based on a 10% uncertainty in the mass of PC clinker and a standard deviation of 0.084 for both 2020 and 2050 (for further details refer to Supplementary Information S1, Section S.4). We randomly sampled these PDFs 1000 times to evaluate the influence of LCA model parameters on the results (Lewandowska et al., 2004), i.e., through a global sensitivity analysis (Plischke et al., 2013). We used a global sensitivity indicator (delta) to define the importance of model parameters on the results, such that when delta equals 1 the results are highly sensitive to the parameter (Borgonovo, 2007). A more detailed description of this uncertainty analysis is provided in Supplementary Information S1 (Sections S7 and S8).

3. Results and discussion

3.1. Portland cement clinker substitution with supplementary cementitious materials

Substituting PC clinker with SCMs (coal fly ash, blast furnace slag, rice husk ash, bagasse ash, calcined clay, limestone) can significantly reduce the climate change impact of cement production by 0.44 kg CO_2-eq. emissions per kg cement over the 30-year period from 2020 to 2050 (Fig. 2), decreasing monotonically with decreasing clinker-to-cement ratio. The potential reduction in climate change impact achieved in 2050 (42%) relative to 2020 is consistent with the results of traditional LCA studies, which report a potential reduction in CO_2-eq. emissions footprint of 34–51% at clinker-to-cement ratios of 50% (Fig. 2) (Miller et al., 2018; Rahla et al., 2019; Arrigoni et al., 2020). The wider range of CO_2-eq. emissions reduction potentials in the existing literature corresponds to different replacement ratios, with higher clinker replacement ratios (up to 90%) resulting in higher impact reductions (~88%). This climate change impact reduction is mainly driven by avoided pyro-processing of limestone in the cement kiln. The contribution of SCM pre-treatment was found to be negligible, except in the case of calcined clay addition where pre-treatment requires significantly higher

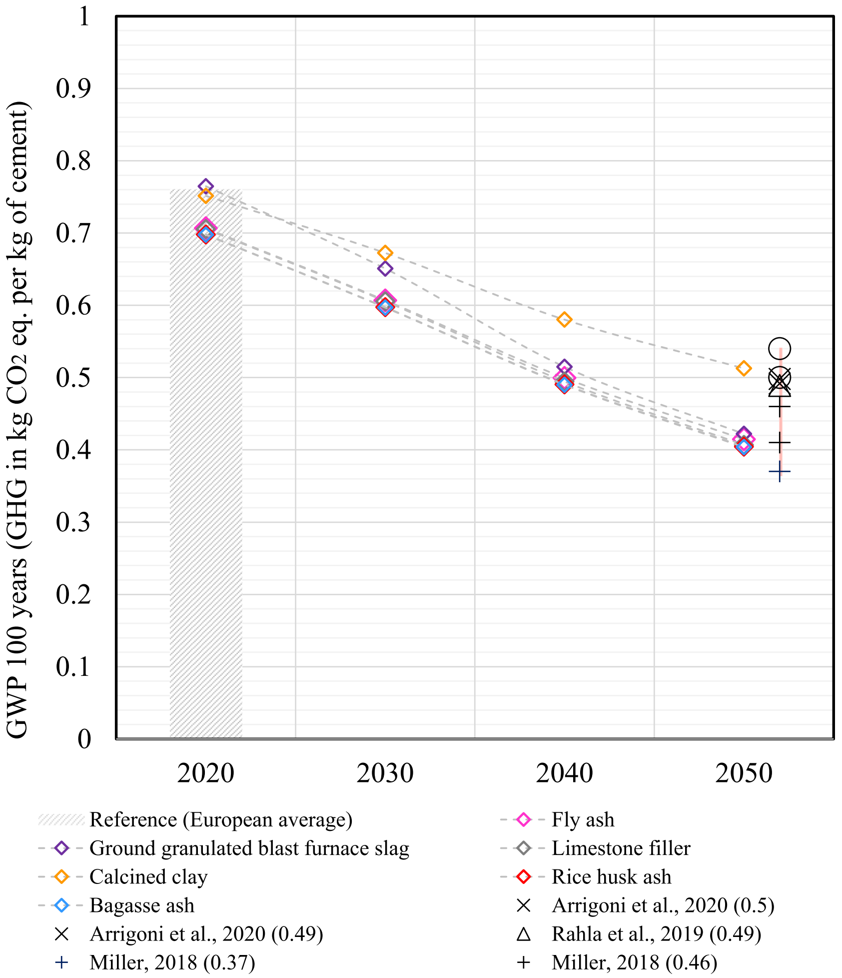

Fig. 2. CO_2-eq. emissions of blended PCs with different SCMs, from 2020 to 2050, using the SSP2 RCP 2.6 background scenario, compared to reported values (for cements with a ~50% clinker replacement ratio) from traditional LCA studies in 2050 (Miller et al., 2018; Miller et al., 2018; Rahla et al., 2019; Arrigoni et al., 2020).

energy demand (Supplementary Information S1, Section S5.1).

The climate change impacts of producing the different PC-SCM cements at the same year and clinker-to-cement ratio lie within 0.1 kg CO_2-eq. emissions per kg cement, which is a smaller difference than the decrease in CO_2-eq. emissions caused by decreasing the clinker-to-cement ratio from 0.8 in 2020 to 0.5 in 2050. Therefore, the PC clinker substitution level has a greater effect on CO_2-eq. emissions mitigation than the type of SCM used. However, blended cement with calcined clay has a noticeably higher climate change impact (0.52 kg CO_2-eq. emissions per kg cement at 2050) than the other SCMs analysed (coal fly ash, blast furnace slag, rice husk ash, bagasse ash, and limestone; 0.42–0.44 kg CO_2-eq. emissions per kg cement at 2050) mainly because of higher energy requirements (thermal treatment at ~600 °C) in calcined clay production.

3.2. *Increasing alternative fuels utilisation*

Utilisation of alternative fuels (biomass, RDF, TDF, hydrogen [NGSR, solar-powered electrolysis, wind-powered electrolysis]) can reduce CO_2-eq. emissions per kg cement by 25% (i.e., from 0.76 kg to 0.57 kg) between 2020 and 2050 (Fig. 3). A minor reduction in CO_2-eq. emissions (i.e., about 4%) was observed from 2020 to 2030 relative to between 2030 and 2040 and 2040 to 2050 (i.e., about 12% and 10%, respectively), which is driven by greater changes in the projected European electricity mix during the latter years (Supplementary Information S1, Section S5.2).

Changes in the electricity mix have a greater effect on the results for alternative fuels that require more electricity i.e., electrification and hydrogen production (through NGSR) (see also Supplementary Information S1, Section S5.2, Figure S6). For example, complete electrification in 2020 would have resulted in a significantly higher CO_2-eq. emissions (1.14 kg) than the reference value (0.76 kg) (Fig. 3, orange

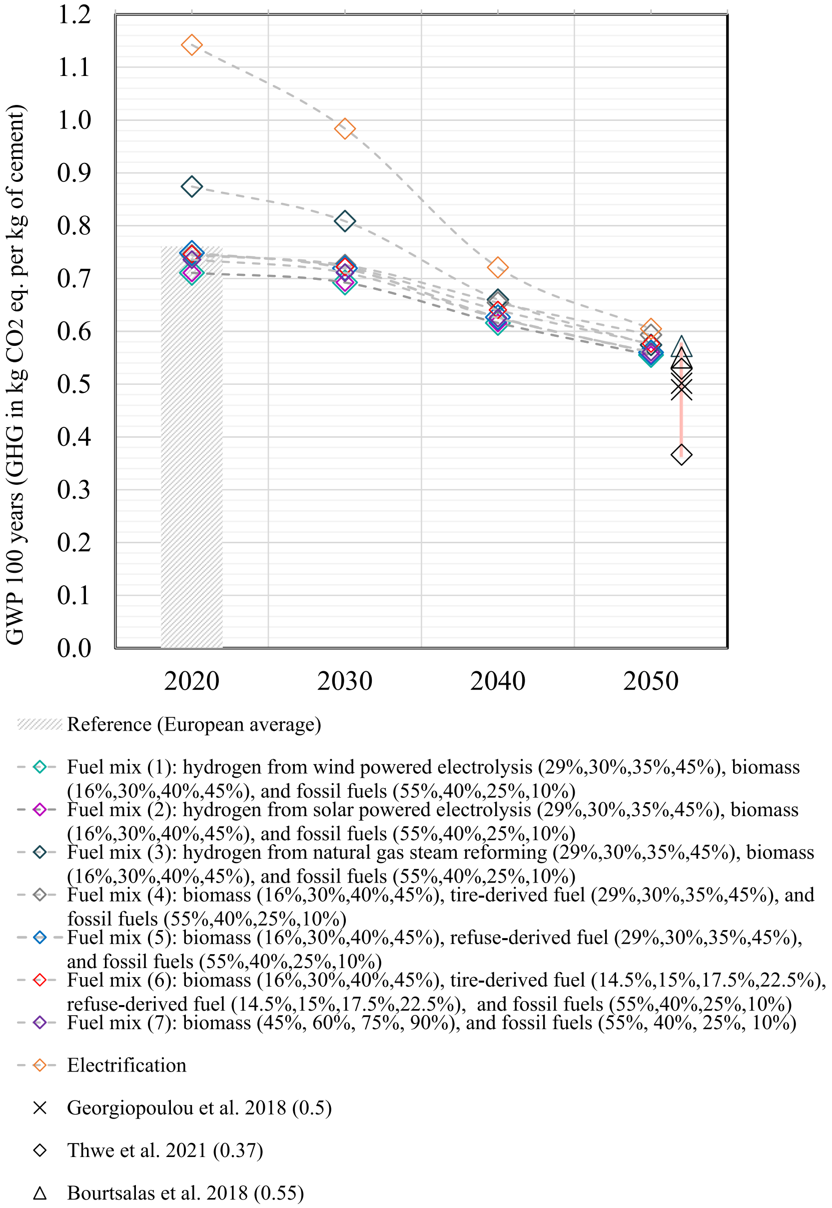

Fig. 3. CO_2-eq. emissions from cement production with alternative fuels, from 2020 to 2050, using the SSP2 RCP 2.6 background scenario, compared to reported values from traditional LCA studies at 2050 (Georgiopoulou and Lyberatos, 2018; (Thanos) Bourtsalas et al., 2018; Thwe et al., 2021). The percentage fuel mix ratio of each individual fuel in 2020 to 2050 is displayed in the figure legend.

diamonds), since electricity was generated mainly from fossil fuels (35%) at this time. Electrification only becomes a viable decarbonisation approach once the amount of fossil fuels used in electricity generation reduces, such that by 2050 electrified cement production has similar CO_2-eq. emissions to other alternative fuels (~0.6 kg CO_2-eq. emissions per kg cement, Fig. 3). Therefore, the potential of electrification in cement production is controlled by the degree of decarbonisation the power generation achieves, causing a higher uncertainty regarding the final emission reduction. The calculated decarbonisation potential of electrification (~30% reduction) is roughly consistent with early results from research on solar energy for raw materials calcination, which showed a 48% potential reduction in climate change impacts where solar calcination was employed instead of conventional (petroleum coke based) calcination (Tomatis et al., 2020)

Fig. 3 shows similar or slightly higher GHG emissions compared to those reported in the literature, mainly due to differences in the foreground unit process data used. For instance, we defined the highest efficiency kiln type to a thermal demand of 3,020 MJ per tonne clinker, which is substantially higher compared to the thermal demand assumed in the work of Georgiopoulou & Lyberatos (2018) of 1,800 MJ per ton clinker. Additional differences are explained by the different fuel mixes modelled here and in the literature. Thwe et al. (2021) investigated the climate change impact of natural gas as a single fuel during combustion, leading to an environmental impact of 0.36 kg CO_2 eq. emissions per kg cement.

The potential CO_2-eq. emissions reduction from use of alternative fuels (Fig. 3, 25% reduction between 2020 and 2050) is lower than that achieved through the SCMs scenario (Fig. 2, 42% reduction between 2020 and 2050), which is consistent with process emissions being the major climate change hotspot in cement production. Overall, the alternative fuels scenario with the lowest GWP100 values combines hydrogen (providing 40% of the thermal demand, generated through wind power), biomass (providing 50% of the thermal demand), and fossil fuels (providing 10% of the thermal demand) (pink crosses, Fig. 3), since this scenario utilises renewable energy sources with inherently low CO_2-eq. emissions.

3.3. Improving kiln configurations

Cement produced with higher efficiency kilns (i.e., 5% [3.68 MJ per kg PC clinker], 10% [3.39 MJ per kg clinker], and 20% [3.02 MJ per kg clinker] reduction in thermal energy demand) resulted in 4%, 9%, and 12% lower CO_2-eq. emissions in 2030, 2040, and 2050, respectively, relative to year 2020 (Fig. 4a). The greatest reduction in CO_2-eq. emissions per kg cement (12%) was observed using the dry process (including a preheater and pre-calciner).

This result is slightly lower than the range of CO_2-eq. emissions reductions reported in the literature (15–20%) (Habert et al., 2010; Benhelal et al., 2013; Chunark et al., 2021). This discrepancy can be explained by differences in assumptions made e.g., the 20% reduction in CO_2-eq. emissions in Benhelal et al. (2013) resulted from a larger improvement in thermal efficiency, by switching from a wet kiln type (5.55 MJ per kg clinker) to a dry kiln configuration (3.00 MJ per kg clinker) than the improvements considered here between a semi-wet/semi-dry kiln (3.68 MJ per kg clinker) and a dry kiln with precalciner and preheater (3.02 MJ per kg clinker).

Introducing a kiln type with higher thermal efficiency has no direct effect on the liberation of CO_2 from clinker calcination reactions, which is the main hotspot of the cement production system. Similarly, higher thermal efficiency reduces fuel consumption but does not change the fuel type. Since this measure does not change the clinker-to-cement ratio nor the fuel type, the 4–12% CO_2-eq. emissions reduction shown in the results are attributable to the reduced fuel demand (Fig. 4b). In 2050, the climate change impact of electricity use is negligible due to decarbonisation of the grid shown by using alternative fuels, e.g., waste plastics.

3.4. Synergistic scenarios

Synergistic implementation of greater PC clinker substitution, higher alternative fuel use, and more efficient kiln types following the IEA and CEMBUREAU roadmaps and without CCS can result in a significantly larger reduction in CO_2-eq. emissions per kg cement (58% by 2050 with SSP2 RCP 2.6) compared to the implementation of individual decarbonisation measures (PC clinker substitution with SCMs, Section 3.1, up to 42%; increasing alternative fuel consumption, Section 3.2, up to 25%; improving kiln configuration, Section 3.3, up to 12%) (Fig. 5).

Our analysis of the effect of allocation on the climate change impact of blended cement containing coal fly ash showed that it is moderately underestimated when no allocation was considered. Performing economic increased the climate change impact by ~20% by 2050 (Fig. 5). The higher impact is attributed to the associated emissions linked to coal combustion at power plants. Reducing trends in climate change impact are observed for both no allocation and economic allocation approaches,

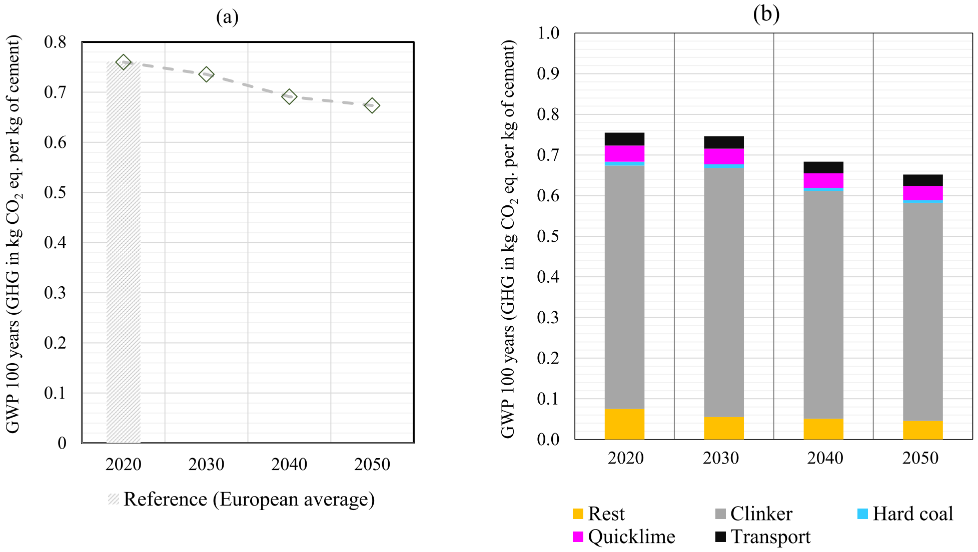

Fig. 4. (a) CO_2-eq. emissions from cement production with several kiln configurations from 2020 (semi-wet/semi-dry) to 2050 (dry with preheater and precalciner), using the SSP2 RCP 2.6 background scenario. (b) Contribution analysis of the key contributing flows from 2020 to 2050 using different kiln configurations.

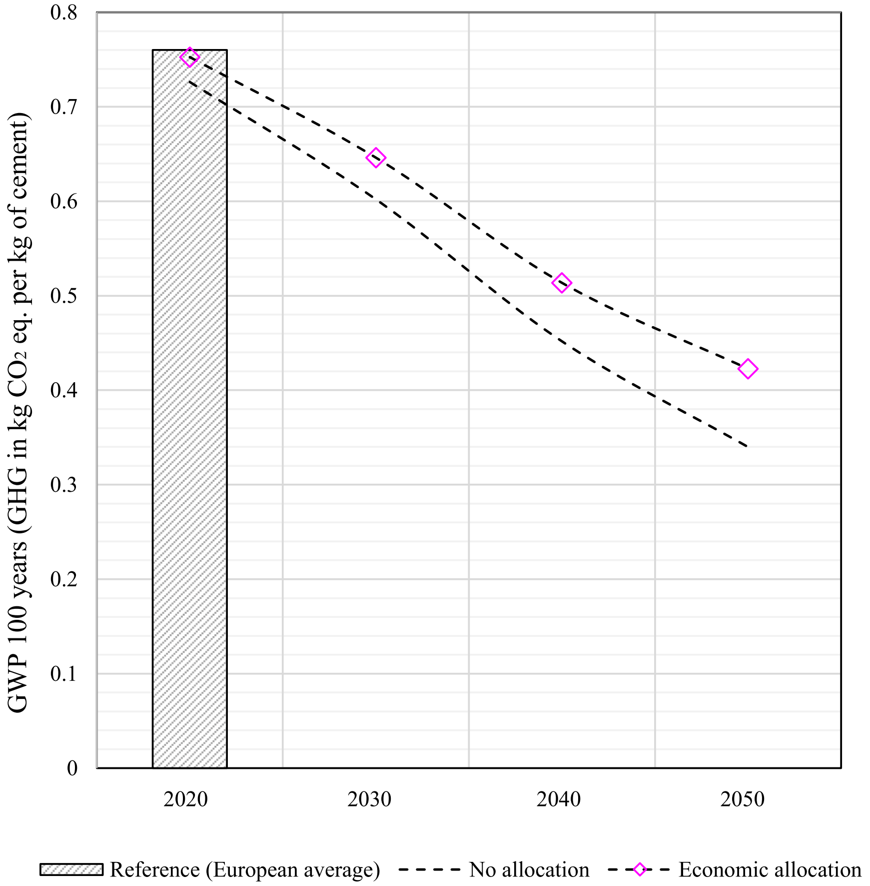

Fig. 5. CO_2-eq. emissions of cement production with (synergistic) scenario 4 from 2020 to 2050, using SSP2 RCP 2.6, for blended PC with coal fly ash, and based on the IEA and CEMBUREAU roadmaps with no allocation and economic allocation approaches.

with 53% and 44% reductions observed from 2020 to 2050, respectively. The low price of coal fly ash (€58 per tonne in 2020) compared to the price of electricity is responsible for the relatively small economic allocation factor (0.0693). This agrees with existing literature, that highlights the importance of including allocation for evaluating the climate change impact effect of SCMs in cement (Shobeiri et al., 2021), particularly at lower clinker-to-cement ratios (Seto et al., 2017).

Fig. 6 shows the climate change impacts of cement production with the synergistic scenarios including PC clinker substitution with coal fly ash (SCMs), increasing alternative fuels utilisation, and improving kiln configurations with (economic) and without allocation of impacts related to coal fly ash production, explicitly showing the contribution of biogenic carbon. As discussed above, no allocation has the lowest climate change impact (0.34 kg CO_2 eq. per kg cement in 2050) while economic allocation shows a higher impact (0.42 kg CO_2 eq. per kg cement in 2050) because of the inclusion of CO_2-eq. emissions associated with electricity generation. The case of no allocation with the reference fuel mix scenario (Fig. 6A) would result in a ~17% higher impact (0.41 kg CO_2-eq. emissions per kg cement) by 2050, compared to the case where increased alternative fuels are used (Fig. 6B). This results from the higher use of fossil fuels in the fuel kiln mix such as petroleum coke and hard coal instead of biomass. It leads to the difference between the amount of biogenic carbon stored in biomass between the two scenarios (0.25 kg CO_2 eq. emissions per kg cement and 0.67 kg CO_2 eq. emissions per kg cement, respectively). Biomass fuel is often considered to have a CO_2-eq. emissions footprint of zero by equating the CO_2-eq. emissions released during the burning of biomass to the CO_2 emissions stored during photosynthesis (growing stage). However, various factors give biomass fuel a non-zero CO_2-eq. emissions footprint. One such factor is that processing is required to form the raw biomass (wood logs) into a fuel feedstock. This processing depends on the biomass source. We account for these (CO_2-eq. emitting and storing) factors here.

The results of the comparative analysis between the IEA/CEMBUREAU and GCCA roadmaps show a minor difference of ~5% between the two scenarios caused by the changes in the fuel mix. Further details on this comparative analysis are provided in Supporting Information S1.

CCS can significantly reduce the climate change impact of cement production (55–88% reduction in GWP100 [0.19 kg CO_2-eq. emissions per kg cement] in 2050 compared to the value in 2020 [0.76 kg CO_2-eq. emissions per kg cement]) (Fig. 7). We calculate CCS to have a slightly higher CO_2-eq. emissions reduction potential by 2050 than that reported in the literature (48–84%) (Volkart et al., 2013; Miller et al., 2018; An et al., 2019; Wang et al., 2022). We attribute this discrepancy to the additional combined effect of decarbonisation measures (i.e., PC clinker substitution with coal fly ash, increasing alternative fuels utilisation, and improving kiln configurations) and our use of background scenarios that includes decarbonisation of the electricity mix, which causes an additional reduction in CO_2-eq. emissions of 6–7% by 2050.

Analysis of multiple CCS technologies (implemented in addition to PC clinker substitution, alternative fuel use, and kiln efficiency improvements) shows that natural gas-powered amine scrubbing without combined heat and power results in a lower climate change impact (0.09 kg CO_2-eq. emissions per kg cement) relative to oxyfuel CCS technology (0.16 kg CO_2-eq. emissions per kg cement) and synergistic scenarios without CCS (0.32 kg CO_2-eq. emissions per kg cement following the IEA/CEMBUREAU roadmaps) in 2050. The results show that the type of fuel used to provide heat for the CCS system has a lesser effect on the overall GWP100 of cement production than the type of CCS technology (Fig. 7). The relatively minor influence of the fuel type for operation of the CCS systems (typically there is a 5% difference between

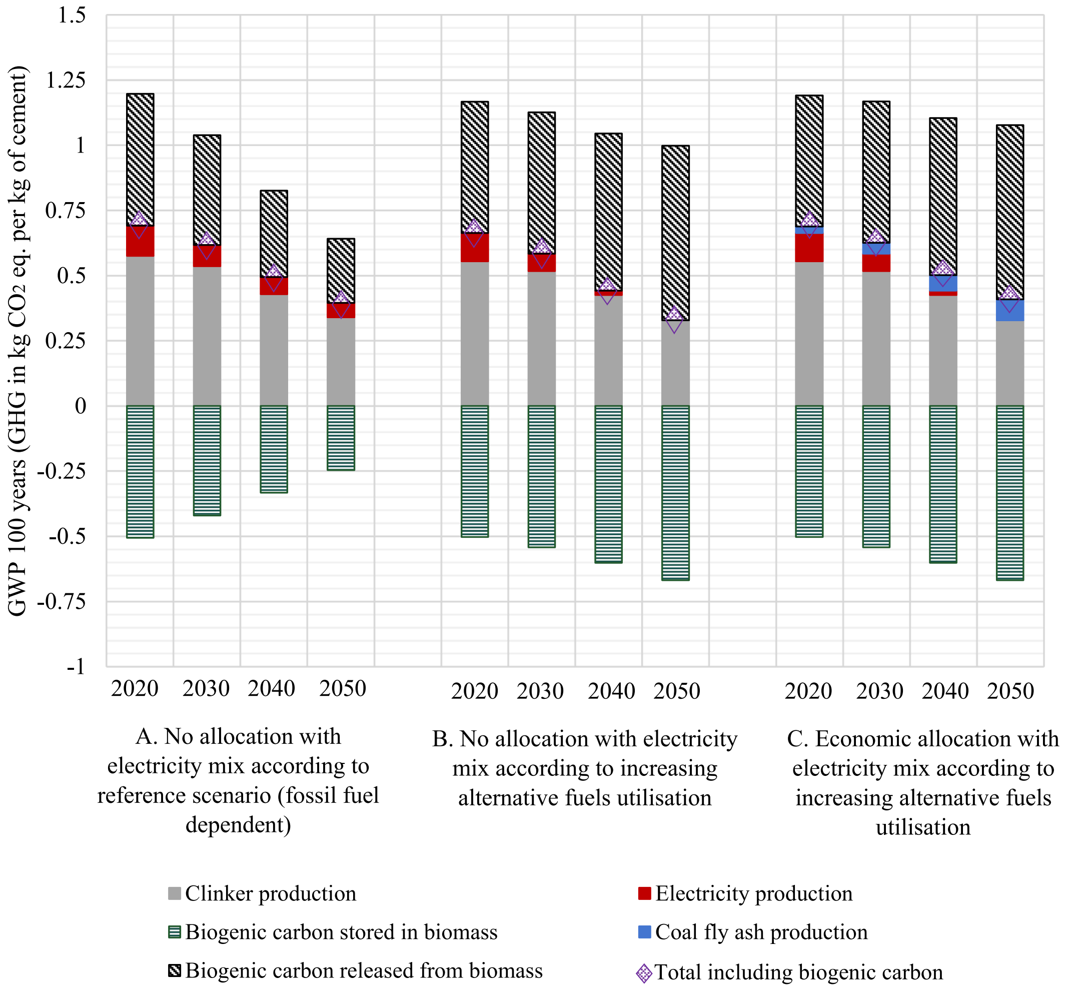

Fig. 6. Contribution analysis for the CO_2-eq. emissions of cement production with synergistic scenarios including PC clinker substitution with coal fly ash, increasing alternative fuels utilisation, and improving kiln configurations from 2020 to 2050 (without CCS) with (economic) and without allocation, and including biogenic carbon.

natural gas and hard coal scenarios) is consistent with the literature, which suggests that the use of natural gas results in slightly lower GWP100 than coal without a combined heat and power plant (Volkart et al., 2013; D. García-Gusano et al., 2015; An et al., 2019; Wang et al., 2022). In the case of integrating a combined heat and power plant to satisfy the thermal demands of the CCS plant, this results in higher GWP100 values relative to direct use of natural gas and coal (Fig. 7). This is because CO_2-eq. emissions arising from the generation of electricity for the CHP system are larger than those from the direct use of natural gas and coal. Amine scrubbing CCS technology results in a lower GWP100 value for cement production than oxyfuel technology due to the higher energy requirements, although both reduce CO_2-eq. emissions relative to cement production without CCS.

Therefore, the results show that CCS can significantly avoid CO_2-eq. emissions from cement production and that the extent of this reduction is modified to a minor-moderate extent by the type of CCS technology (10–18% change) and its fuel type (5–10%). This is consistent with the previous work that studied the implementation of carbon capture technology (without CHP) in the power generation industry including background changes and found that the type of CCS technology is more influential (7%) than fuel type (3%) in reducing GHG emissions (Volkart et al., 2013). Our findings indicate that reducing the CO_2-eq. emissions from cement production to contribute to limiting the temperature rise to 2 °C by 2100 relative to pre-industrial levels (requiring 0.72 kg CO_2-eq. emissions per kg cement) is achievable without CCS, but with substantial increase of alternative fuels and PC clinker substitution with SCMs i.e., 90% alternative fuel mix and 50% PC clinker substitution. Additional decarbonisation measures such as CCS are needed to reduce its GWP100 further, possibly down to 0.09 kg CO_2-eq. emissions per kg cement by 2050 using amine scrubbing CCS technology.

3.5. *Effect of background scenarios*

The SSP2 baseline scenario shows a smaller CO_2-eq. emissions reduction than the SSP2 RCP2.6 scenario (Fig. 8). The two SSP2 background scenarios show similar CO_2-eq. emissions per kg cement values at year 2030 (~0.6 kg CO_2-eq. emissions per kg cement). However, by 2040, the influence of the background system becomes significant, such that the difference between the SSP2 baseline and RCP 2.6 scenarios are 6% in 2040 (0.46 vs. 0.43 kg CO_2-eq. emissions per kg cement, respectively) and 10% in 2050 (0.36 vs. 0.32 kg CO_2-eq. emissions per kg cement, respectively).

The difference in CO_2-eq. emissions per kg cement between the background scenarios is associated with the composition of the future electricity mix. For example, in the SSP2 RCP2.6 background scenario, the electricity mix contains more wind power than in the SSP2 baseline scenario, reducing its GWP100 to 0.34 kg CO_2 eq. emissions per kg rather than 0.39 kg CO_2 eq. emissions per kg respectively. Thus, even though PC clinker substitution is a key driver of CO_2-eq. emissions, our results show that the electricity mix and thus changes in the background system are significant when SCM pre-treatment requires high amounts of electricity (Supplementary Information S1, Figure S4).

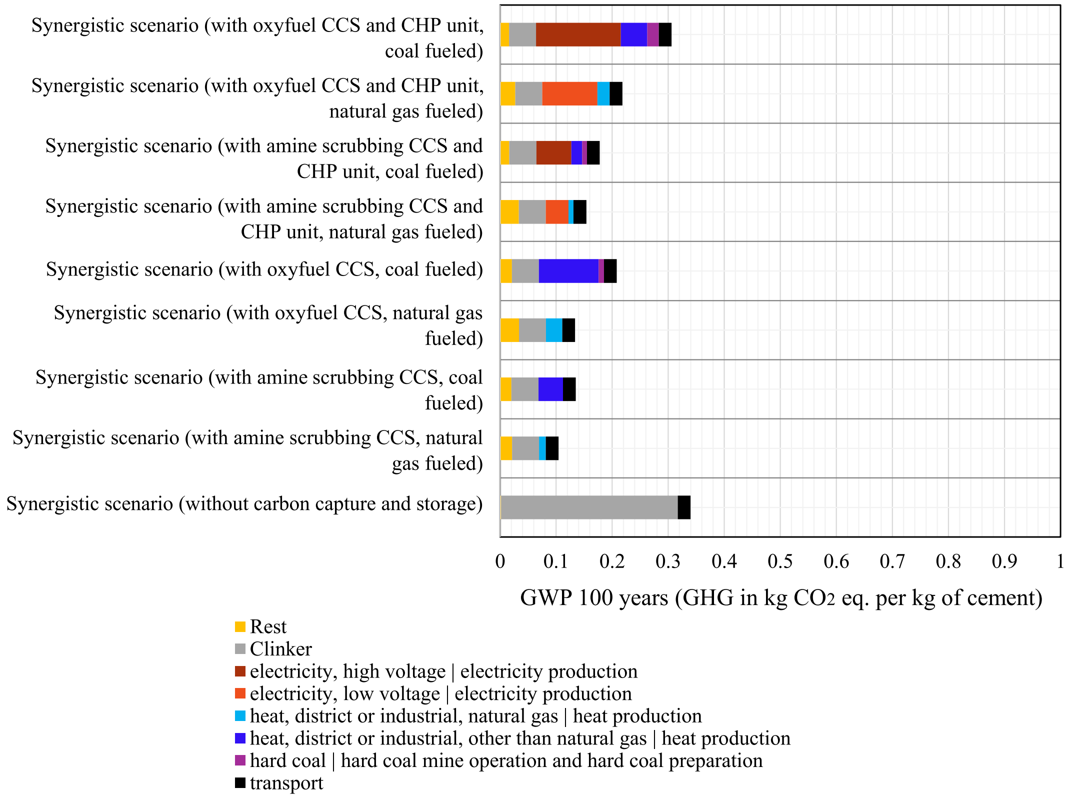

Fig. 7. Contribution analysis showing CO_2-eq. emissions of cement production developed based on the IEA and CEMBUREAU roadmaps with synergistic scenarios including PC clinker substitution with SCMs, alternative fuel use, improved kiln configurations, and CCS technologies (i.e., amine scrubbing, oxy-fuel) at 2050, with and without combined heat and power unit (CHP).

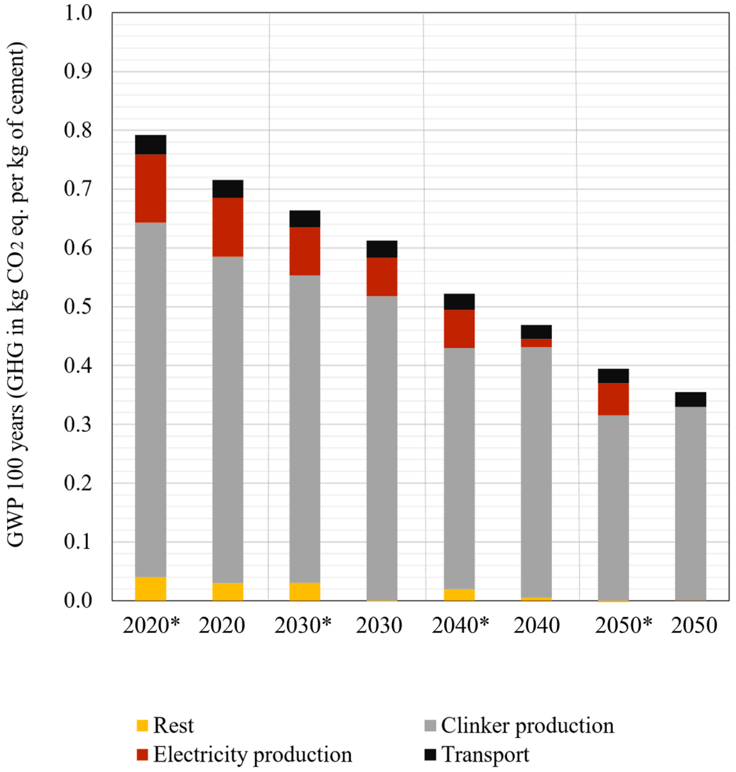

Fig. 8. CO_2-eq. emissions of cement production from a synergistic scenario developed based on the IEA and CEMBUREAU roadmaps, incorporating PC clinker substitution with coal fly ash, increasing alternative fuels utilisation (fuel mix consists of hydrogen generated through wind power, biomass, and fossil fuels), and improving kiln configurations from 2020 to 2050 (without CCS), with SSP2 baseline (presented with an asterisk *) and SSP2 RCP 2.6 (no asterisk).

3.6. Challenges for global decarbonisation of cement production

A key challenge for global decarbonisation of cement production is the capital investment required to retrofit carbon capture and storage technology. The scale of this challenge depends on the individual company and country, according to local and regional opportunities and incentives. Local conditions are a driving force for controlling the rate and extent of decarbonisation, since variations in government regulations, electricity mixes, market sizes, raw material availabilities, and logistics influence the operational conditions in each production facility. Construction practices and acceptance, including standards, are additional parameters that differ from region to region and influence the adoption of novel and alternative composite Portland cements. These issues make global decarbonisation of cement production a complex task (IEA, 2018).

4. Conclusions

This study has shown that PC clinker substitution alone could reduce CO_2-eq. emissions per kg cement by 42% between 2020 and 2050, whereas alternative fuels (25%) and kiln types (12%) also reduce CO_2-eq. emissions but to lesser extents. Combining all three individual measures leads to 58% reduction in CO_2-eq. emissions per kg cement by 2050 relative to its value in 2020 (i.e., 0.76 kg CO_2-eq. emissions per kg cement). This level of CO_2-eq. emissions reduction is sufficient to meet the targeted 24% reduction in line with the Paris Agreement and is achievable irrespective of technology roadmap followed: IEA/CEMBUREAU or GCCA (minor difference ~5% in CO_2-eq. emissions). These results involve significant increases in use of biomass fuels, and an area for future research is to investigate the effect of this on other impact categories, particularly land use.

CO_2-eq. emissions from cement production could be further reduced by combining individual decarbonisation measures with CCS. Implementing all three individual decarbonisation measures and CCS (amine scrubbing) together could lower CO_2-eq. emissions to as low as 0.09 kg CO_2-eq. emissions per kg cement in 2050. Cement production with amine scrubbing was found to have lower CO_2-eq. emissions than oxyfuel technology regardless of fuel type, while the addition of a CHP plant for CCS led to an increase in CO_2-eq. emissions for both (amine scrubbing and oxyfuel) CCS technologies.

Accounting for future changes in the electricity mix in LCA studies of cement production, which we modelled here via changes in the background database to reflect the general trend in decarbonising the electricity mix over time, is significant since it reduces calculated CO_2-eq. emissions per kg cement by ~10%. The importance of a prospective LCA approach through scenario analysis of cement-related technology developments and additional changes in the economic system, such as the energy transition, in assessing the future decarbonisation potential of conventional cement and concrete production with emerging technologies is highlighted.

Supplementary information

The following two files are provided as Supplementary Information:

A PDF that includes the life cycle inventory for the decarbonisation measures (SCMs, alternative fuels, kiln configurations and thermal efficiencies, and carbon capture and storage technologies). Baseline (background) scenario results and analysis and global sensitivity analysis are also included.

A Microsoft Excel file that includes the foreground scenarios developed according to the decarbonisation measures studied and the corresponding changes in 2020, 2030, 2040, and 2050.

CRediT authorship contribution statement

Maria Georgiades: Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Izhar Hussain Shah:** Writing – review & editing. **Bernhard Steubing:** Methodology, Data curation, Writing – review & editing. **Christopher Cheeseman:** Writing – review & editing. **Rupert J. Myers:** Conceptualization, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Rupert J. Myers reports financial support was provided by European Commission. Rupert J. Myers reports equipment, drugs, or supplies was provided by Engineering and Physical Sciences Research Council.

Data availability

Data will be made available on request.

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Supplementary materials

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