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Life cycle assessment of the climate change impact of magnesium phosphate cements formulated with tundish deskulling waste compared to conventional cement

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ABSTRACT

Ordinary Portland cement (OPC) production significantly contributes to greenhouse gas emissions due to high resource consumption and CO_2 output. It is therefore imperative to investigate alternative cements, such as magnesium phosphate cement (MPC), as a potential solution. This study is based on Life Cycle Assessment (LCA) methodology, comparing OPC with alternative magnesium phosphate cements (MPC) developed at the laboratory scale. The novelty of this study considers two types of alternative cements that use two different sources of MgO: MPC-MgO, developed with pure MgO, and MPC-TUN, formulated using tundish deskulling waste from steelmaking industry.

The evaluated functional units are 1 tonne of cement, 1 m^3 of cement paste, and 1 m^3 of mortar, all of them are designed for the same function, which is as non-structural precast elements. The study assesses climate change impacts under two future scenarios: 1) electricity decarbonisation in the background economy using projections from Integrated Assessment Models and 2) electricity decarbonisation and a fuel switch in the cement kilns.

The results indicate that MPC-TUN exhibits a lower impact of climate change in terms of CO_2 emissions across all functional units and scenarios compared to the other materials. In the most ambitious climate scenario, MPC-TUN mortar exhibits 42% and 56% lower climate change impacts than OPC-CEM I and MPC-MgO mortars, respectively, demonstrating its potential as a more sustainable construction material. Although further research is needed on the applicability of MPC-TUN in construction, regulatory frameworks are advised to simplify barriers to expedite the adoption of sustainable alternative cements.

1. Introduction

The construction sector, which provides the infrastructure needed for our society's daily activities, is accountable for approximately 40% of the total natural resources utilized, and 40% of the total energy consumed by humans (Eberhardt et al., 2020; Gong et al., 2012). Additionally, the construction sector is responsible for generating approximately 40% of the total waste produced by

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human activities (Gong et al., 2012). Given the high resource and waste intensity of this sector, it is essential to alter the trajectory of the construction sector to minimize the associated environmental impacts (Hossain and Poon, 2018).

Cement, a fundamental and essential component in concrete, is a crucial material for the construction sector. Ordinary Portland cement (OPC) possesses various advantages, such as its affordability, mechanical properties, durability, and more (Valipour et al., 2014). Currently, conventional cement is a major contributor to climate change (Folliet and Milagros Rivas Saiz, 2017). Specifically, the cement industry is accountable for 8% of anthropogenic carbon dioxide (CO_2) emissions, primarily originating from two main contributions: the calcination process to obtain clinker and the energy consumption during manufacturing (Sousa et al., 2023). In response to the demand for OPC and its associated impact, the industrial community has established a roadmap to achieve Net Zero CO_2 emissions by 2050 (International Energy Agency, 2023; de Brito and Kurda, 2021; El-Dieb and Kanaan, 2018). This roadmap is based on the "Focus of the 5Cs", which encourages collaboration throughout the entire value chain of "Clinker-Cement-Concrete--Construction-(re)Carbonation" to realize climate neutrality in the industrial sector (Agrupación de fabricantes de cemento de España, 2021; CEMBUREAU, 2021).

CEMBUREAU, the European Cement Association, has developed a roadmap for 2050 that outlines the opportunities and actions depicted in Fig. 1 (CEMBUREAU, 2021). The aim of this roadmap is to reduce the emissions along the value chain by 2030 by 30–40% compared to 1990 and to achieve carbon neutrality by 2050. Particularly, Fig. 1 outlines CO_2 emissions reductions for each 5C by 2030 and 2050, aiming to achieve zero CO_2 emissions per tonne of cement produced in 2050. These targets align with various policies of the European Union (EU), in line with the Paris Agreement's objective of limiting the global temperature increase to well below 2 °C and striving to achieve 1.5 °C, as well as other agreements (Amanatidis, 2019; Anna Nilsson et al., 2020; Brugger et al., 2021). The successful achievement of these goals relies on the implementation of different regulations and policy frameworks, along with investments in technologies that are currently being undertaken at local, national, and international levels.

When it comes to cement, there are conventional options available that utilize alternative materials such as blast furnace slag (BFS) from the steel industry and fly ash (FA) from coal-fired power plants, resulting in a lower clinker content. However, the replacement potential of these conventional substitution materials is limited in the future as the processes, of which they are by-products, are expected to decline in a future decarbonized economy (Font et al., 2020; Kermeli et al., 2019). Additionally, there are supplementary cementitious materials (SCM) options available, as well as other alternative binders (Kermeli et al., 2019). One such alternative binders is magnesium phosphate cement (MPC) (Formosa et al., 2012; Huete-Hernández et al., 2021; Maldonado-Alameda et al., 2017). MPCs is produced by combining magnesium oxide (MgO), monopotassium phosphate (MKP, KH_2PO_4), and water.

In the last decades, circular economy has emerged as another mean to reach environmental sustainability, by minimizing material waste and maximizing material reuse at all stages of production and consumption(Ma et al., 2023). Utilizing waste as a raw material instead of extracting natural resources is an important strategy to reduce landfill waste and decrease the extraction of new natural resources. As a result, there is a growing body of research focused on developing alternative cements that utilize waste as a raw material, aligning with new environmental policies (Giro-Paloma et al., 2019; Huete-Hernández et al., 2021; Maldonado-Alameda et al., 2018). This study compares magnesium phosphate cement (MPC) formulated with pure magnesium oxide (MPC-MgO) to MPC-TUN which uses refractory waste from the steel industry, specifically tundish deskulling waste (TUN), as a source of magnesium oxide. TUN is a refractory material used in the last metallurgical vessel through which liquid steel flows before being shaped (Formosa et al., 2012).

Life cycle thinking is a valuable tool for addressing social, economic, and environmental challenges. To comprehensively examine the various impacts of conventional and alternative cements, a life cycle assessment (LCA) approach is necessary. LCA has been widely used to assess the environmental impacts throughout the life cycle of a product or system. Different approaches to LCAs exists, contingent upon the study's objectives. Conventional LCA is structured around current environmental impacts derived from historical

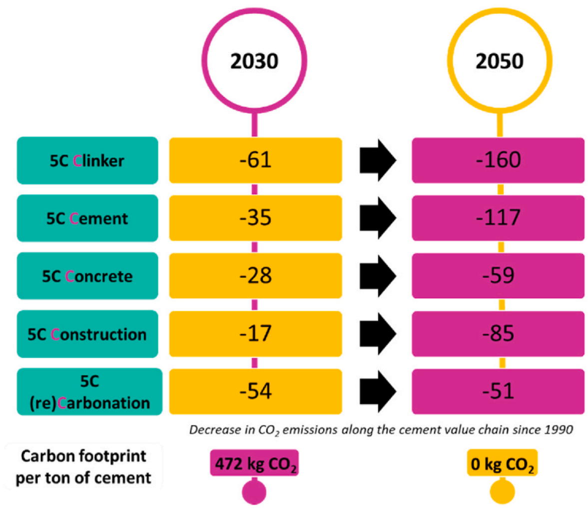

Fig. 1. CEMBUREAU 2050 roadmap related to the CO_2 savings for each 5C (adapted from (CEMBUREAU, 2021)).

or present data, while prospective LCA (pLCA) is oriented towards future scenarios, considering potential alterations that may happen (Arvidsson et al., 2018). Hence, pLCA offers the opportunity to assess whether an alternative cement can be classified as sustainable or not considering future developments (Langkau et al., 2023; Mendoza Beltran et al., 2020; Sacchi et al., 2022). PLCA is particularly beneficial for evaluating the environmental performance of emerging materials that have not yet been widely implemented.

The objective of this study is to compare the differences in current and potential future climate change impact and energy consumption by employing both conventional LCA and scenario-based pLCA for three cement types (OPC, MPC-MgO, and MPC-TUN) in the three essential formats (cement, cement paste, and mortar). Future changes are modelled by incorporating anticipated alterations in future electricity and heat usage within the processes of the evaluated materials. This research helps to understand and compare the emission reduction potential offered by innovative cements compared to conventional cements (Fig. 2), allowing environmental hotspots to be identified. It also provides valuable insights to guide the future development of sustainable materials in the cement industry.

2. Raw materials

The environmental impact of conventional cement is compared to other types of cements for the application as cement, cement paste, and mortar, all of which have been prepared following the UNE EN 196-1 standard (Normalización Española, 2018). The different products evaluated are.

- OPC CEM I 52,5 R.
- MPC formulated with pure MgO: MPC-MgO.
- MPC formulated with TUN as MgO source: MPC-TUN.

Clinker is the major component of OPC, simultaneously contributing the most to its emissions. The quantity of clinker used, and the types of materials employed are regulated by international standards, ensuring that cement is a standardized product that meets rigorous specifications for constructing durable structures with long lifetimes. Substituting clinker with alternative materials requires that the final product possesses similar mechanical and durability properties, as well as high availability. Rules and regulations play an important role in approving the introduction of new cements into this sector (Griffiths et al., 2023; Guo et al., 2024; Wang et al., 2021).

MPC-TUN is at Technology Readiness Level 3 (TRL3), indicating that it is a laboratory-scale development and not yet a fully mature technology (Alfocea-Roig et al., 2023). On the other hand, OPC CEM I, and MPC-MgO are at TRL9 because they are currently commercially available cements. Previously, a preliminary study was conducted to evaluate the properties of MPC-TUN, and the results showed that it possesses the necessary qualities for construction applications (Alfocea-Roig et al., 2023). Therefore, this study assumes that MPC-TUN can be used commercially, enabling a comprehensive comparison and full-scale environmental assessment (Batuecas et al., 2021).

3. Methodology

LCA is a tool utilized for analysing and assessing the environmental impacts of a product or service. By highlighting emission hotspots and comparing impacts between alternatives, the LCA methodology allows consumers and producers make more sustainable product choices.

This study was conducted following four primary stages (Pryshlakivsky and Searcy, 2013).

A. **Goal and scope:** This stage involves defining the main goal and determining the system boundary.
B. **Life cycle inventory (LCI):** In the LCI stage, data collection and calculations are performed to quantify the input and output of materials and energy.

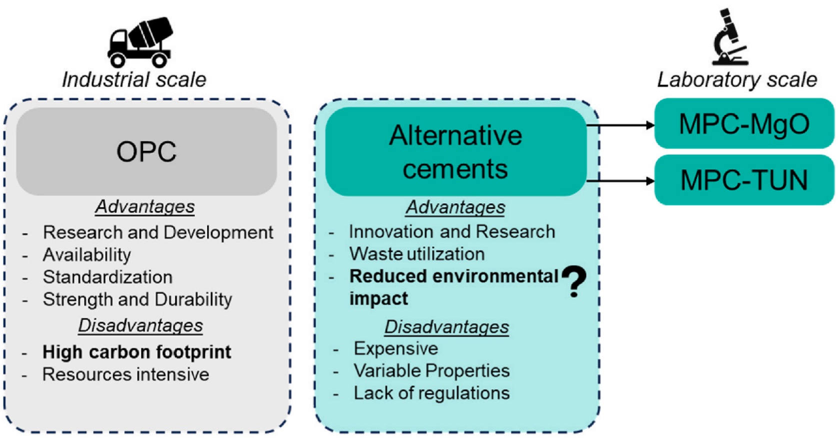

Fig. 2. Advantages and disadvantages of OPC and alternative cements under investigation.

C. **Life cycle impact assessment (LCIA):** During the LCIA stage, the potential environmental impact obtained from the LCI is evaluated.
D. **Interpretation:** The interpretation stage involves drawing conclusions based on the environmental impacts while considering the previously established objectives.

3.1. Goal and scope

The main goal of this study is to perform an LCA to compare the carbon footprint of different cements for construction applications. Consequently, the study aims to assess and compare the environmental impacts of OPC-CEM I, MPC-MgO, and MPC-TUN to identify the environmental hotspots.

The functional unit serves to quantify the specific product characteristics and defines the functions to be analysed (Batuecas et al., 2021; Panesar et al., 2017). In this study, three functional units are examined: 1 tonne of cement (dry powder), 1 m^3 of cement paste, and 1 m^3 of mortar. Three basic components are evaluated to cover the many commercialization strategies of cement: it is marketed as dry cement, which functions as a binder (cement paste), or as mortar for non-structural precast element. Although all three functional units are considered for impact assessment, particular attention will be given to the results obtained for 1 m^3 of mortar, which is a mix of cement, sand, and water, since mortar is a versatile material widely used in the construction industry. However, the functional unit of 1 m^3 of mortar allows to standardize the comparison between different materials and to enhance understanding of their carbon footprint impact per volume unit for the same applicability, which is an approach used within the research field. The geographical context of the study is the European Union (EU), and the time horizon is 2020–2050. This attributional LCA study uses the Ecoinvent 3.9 cut-off database.

The study adopts the Cradle-to-Gate system boundary. This system boundary considers the flow of materials, energy, and emissions from raw material extraction until manufacturing, excluding use and end of life. In addition, in this study, transport has not been considered, since it has been estimated that all materials are manufactured in the same location. It is important to note that the mixture design is tailored to the functional unit, resulting in different proportions of raw materials. However, despite the variations in proportions, all materials exhibit the essential properties to be applied by the same application. A fundamental prerequisite for materials intended for use in the construction industry is that they possess identical workability characteristics, among other requirements. Hence, the water/cement (W/C) ratio of these materials has been carefully adjusted to obtain a similar consistency during casting, i.e. moderate slump.

3.1.1. Future scenarios

The conducted LCA takes a prospective approach, for which it focuses on the anticipated evolution of the heat supply in cement industry and worldwide transformations in the global electricity sector related to sustainable development (Georgiades et al., 2023; Maes et al., 2023; Müller et al., 2024). The scenario development and analysis in this study are explorative, as it seeks to answer the question of how the situation in this sector could change if this alternative were to be introduced. Currently, this possibility is considered as a future simulation, although it has not yet been established as mandatory compliance regulations for the coming years.

The LCI is studied under policy scenarios for 2020, 2030 and 2050. Therefore, it is necessary to update and modify the Life Cycle Inventory database with respect to energy, efficiency, and other relevant factors based on these future pathways.

Specifically, this study focuses on the changes in emissions from conventional and alternative cements resulting from the use of alternative fuels and alternative electricity supply. The scenarios selected for each type of cement are based on the energy vision 2050 studies (Brugger et al., 2021). Two types of scenarios were evaluated.

1. **Electricity scenario**
   Scenarios that consider only the evolution of electricity production in cement production and the wider economic background system (Mendoza Beltran et al., 2020).
2. **Fuel and electricity scenario**
   Combined modelling of the background electricity scenario with foreground scenarios concerning fuel switch, developed by the decision-maker conducting the LCA (International Energy Agency, 2021).

Regarding the electricity scenario, this study considers multiple scenarios based on the Shared Socioeconomic Pathways (SSPs), which describe different potential future development pathways based on different assumptions about population, socio-economic conditions, energy use, and technology advancements (Riahi et al., 2017). Out of the five SSPs available, only SSP2 is considered in this study, as it represents a medium-level challenge for mitigation and adaptation, following the current development pathways (How 'Shared Socioeconomic Pathways, 2018; Meinshausen et al., 2020). The Representative Concentration Pathways (RCPs) are used to describe various levels of GHG (greenhouse gas) emissions that could occur in the next century. In this study, the Integrated Assessment Model (IAM) REMIND (REgional Model of Investments and Development) is employed for the electricity scenario (Potsdam Institute for Climate Impact Research, 2023; REMIND, 2023). The different IAM pathways evaluated are as follows.

- SSP2-Base (resulting in an increase of 3.5 °C by 2100): in this scenario, society and economic trends are projected based on historical developments, without considering any specific additional climate policy using the most recent projections of the European Commission and PRIMES (Price-induced market equilibrium system) projections, as the reference for energy consumption (Castillo et al., 2022).
- SSP2-RCP1.9 (resulting in an increase of 1.5 °C by 2100): this scenario extrapolates society and economic trends from historical developments while aligning with the climate policy objectives outlined in the Paris Agreement.

In addition to assessing the isolated influence of a decarbonized electricity system in the electricity scenarios, a second set of scenarios combines these with changes is future thermal fuels. In these joint scenarios, the same assumptions from REMIND for electricity are taken as in electricity scenario, and the fuel assumptions are presented in Table 1. It is important to highlight that in 2020 no alteration in the fuel mix has been accounted for, and the data solely encompasses the information from the preceding scenario (electricity scenario). Future fuel scenarios are considered by adapting fuel types from cement roadmaps and altering the fuel sources for the main sub-processes integrated into the database (Brugger et al., 2021; CEMBUREAU, 2021). In practice, it is assumed that the heat market is shared between cement manufacturing and the production of chemical reagents. Table 2 summarizes the combination of scenarios of this study.

3.2. Life cycle inventory analysis (LCI)

3.2.1. OPC-CEM I

OPC CEM I is frequently used for structures, products, and pavements in areas with low concentrations of sulphate ions in groundwater or soil. Among all the OPC families, CEM has been selected, as it is suitable material to be used as a non-structural precast element. Its composition consists of 95 wt% of clinker and 5 wt% of gypsum (Real et al., 2021). Fig. 3 illustrates the raw materials used of OPC-CEM I and the MPC-cements for the different functional units evaluated in this study, which was conducted based on data from both the literature and laboratory studies (Niewiadomski et al., 2021). Furthermore, it is possible to observe the raw materials utilized, the material density, and the water/cement (W/C) ratio.

Fig. 4 shows the flowchart to produce 1 m^3 of OPC mortar, with all steps passing through the stages of cement and cement paste and their respective functional units. It visually represents the different materials used in the cement mix and displays the various processes involved in obtaining clinker (95% of the total of OPC-CEM I). The main stages are.

- The acquisition of raw materials, which primarily involves sourcing limestone and clay.
- Quartering, grinding, and milling processes are employed to homogenize the raw materials and reduce their particle size.
- Preheating and calcination are carried out to induce a series of reactions that result in the formation of clinker.

3.2.2. MPC-MgO

MPC-MgO is conventionally produced using 22.85 wt% of pure MgO, and 77.15 wt% of MKP. Fig. 3 presents the raw materials of MPC-MgO for the different functional units examined. To achieve workability and consistency comparable to MPC-TUN, and considering the specific requirements and characteristics of the pure MgO used, a higher W/C ratio was selected than typically recommended in the literature (Ma et al., 2014; Meng et al., 2023). Additionally, the use of boric acid as a retarder was not required due to the different material requirements for the same application.

Currently, magnesium oxide is obtained from the calcination of magnesite ($MgCO_3$), resulting in the generation of 1.55 tonnes of CO_2 per ton of MgO produced (Ellis Gartner A, 2018). The specific type of magnesium oxide used in the development of MPC is referred to as Dead-Burned Magnesia (DBM) or sintered magnesia. DBM is obtained through another high-temperature calcination of magnesium oxide at approximately 1500 °C, which consumes 6546 MJ per one tonne of DBM (Mathias, 2009). This calcination process ensures the desired chemical reactivity characterized by low reactivity MgO and reduces the specific surface area (An et al., 2018; Luong et al., 2018; Ruan and Unluer, 2016; Sinka et al., 2018).

Fig. 5 shows the flowchart of the production of 1 m^3 of MPC-MgO mortar, including the MPC-MgO cement and cement paste stage. The flowchart includes the two-step calcination to obtain DBM and the other required materials (monopotassium phosphate, sand, and water).

3.2.3. MPC-TUN

In this case, the magnesium oxide source is obtained from tundish deskulling waste (TUN), which is a waste derived from steel manufacturing. This study incorporates the conditioning process required to transform TUN into useable raw materials with the desired quality and particle size for its use as a cement component. Magnesitas Navarras, S.A., a company located in Navarra (Spain), has provided information on the TUN conditioning process, starting from when it is considered waste until it is revalued as a primary component of MPC-TUN. The conditioning process involves screening, grinding, magnetic separation, and mixing, which are observed in Fig. 6. Based on the data supplied by the companies, the conditioning process is approximated to consume 64 kWh per tonne of TUN. These companies focus their activity on the recovery of refractory material from all types of industrial furnaces, for this reason, it is estimated that the values provided are reliable. The other raw materials used in MPC, being commercial materials, do not require a conditioning process. MPC-TUN is produced by combining 60 wt% of TUN with 40 wt% of MKP (Alfocea-Roig et al., 2023). Additionally, 1 wt% of boric acid (HB) is added to the total solid weight to enhance workability and delay the setting time. Fig. 3 shows the MPC-TUN raw materials, revealing the ratios derived from previous laboratory-scale studies. The DIOPMA research group has

Table 1
Heat fuel generation mix (Brugger et al., 2021; CEMBUREAU, 2021).

Type	2030 (%)	2050 (%)
Coal	30	0
Fuel oil	10	10
Biomass	30	50
Bio propane (GPL)	30	40

Table 2
Overview of scenario combinations.

	Electricity sector projections	Fuel mix projections
Electricity BAU	SSP2-Base (REMIND)	–
Electricity 1.5 °C	SSP2-RCP1.9 (REMIND)	–
Electricity and fuel BAU	SSP2-Base (REMIND)	Heat fuel mix, see Table 1
Electricity and fuel 1.5 °C	SSP2-RCP1.9 (REMIND)	Heat fuel mix, see Table 1

BAU (Business as usual); SSP2-Base1.5 °C; SSP2-RCP1.9.

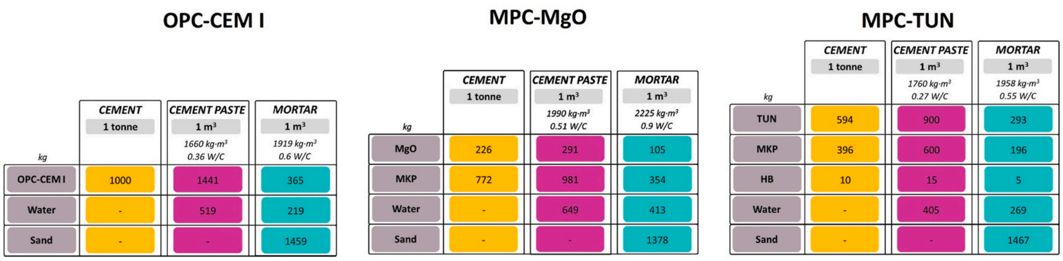

Fig. 3. Raw materials used in the functional units of the evaluated materials (see Appendix A, Table A.1).

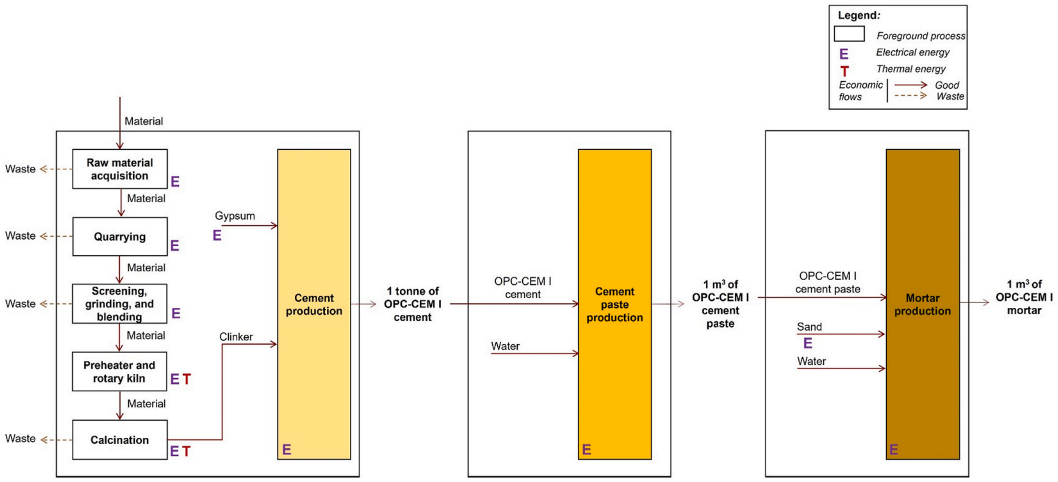

Fig. 4. OPC-CEM I flowcharts of the functional units assessed (see Appendix A, Table A.1).

considerable expertise in this field, having devoted extensive years to the advancement of MPCs.

It is essential to highlight that the collection of this data was difficult due to the low TLR of MPC-TUN. Particularly, data on the electricity consumption for an industrial-level conditioning of TUN was lacking and these gaps were filled with contains various assumptions. These data gaps have the potential to underestimate the ultimate results concerning the future production of this product. However, it is anticipated that the deviation from reality will be minimal, given that the assumptions have been carefully aligned with real-world conditions.

Allocation involves assigning the input and/or output streams of a multifunctional process to the product system under evaluation (H. A. Aguirre-Villegas et al., 2012; Heijungs and Guinée, 2007). In this case, allocation by cut-off is applied to divide the impacts of TUN between steel production and its later use in MPC-TUN. This means that the upstream impacts of TUN are counted towards steel, while the conditioning process to turn the TUN waste into a raw material is counted towards the cement life cycle (Turk et al., 2015). In other words, as depicted in Fig. 6, the TUN comes as a burden-free waste from the steel industry and is considered as a good after it undergoes conditioning, making it suitable for use as a magnesium source.

3.3. Life cycle impact assessment (LCIA) methods

The outcomes of the LCA are dependent on the choices and assumptions made regarding the data and methods employed. The specific impact category considered is the same across in both scenarios, which is.

- Climate change:

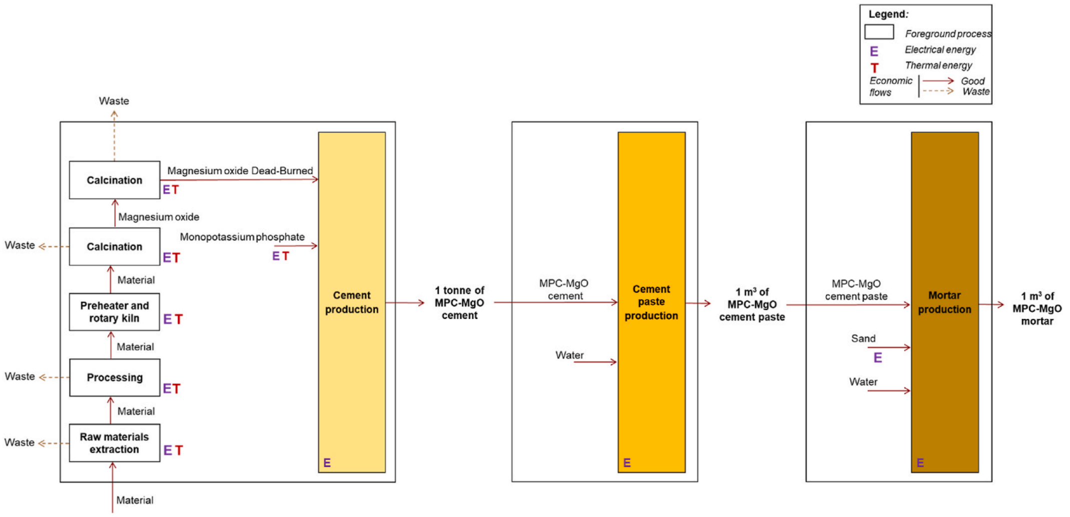

Fig. 5. Flow diagrams of the MPC-MgO functional units evaluated (see Appendix A, Table A.1).

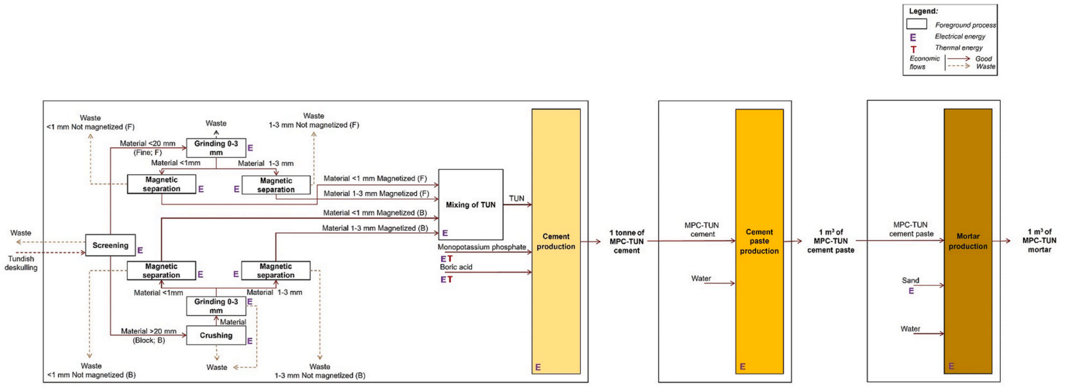

Fig. 6. Flow diagrams of the MPC-TUN functional units evaluated (see Appendix A, Table A.1).

o Global warming potential (GWP 100): this indicator quantifies the potential for global warming over a 100-year timeframe. The unit used is kg $CO_{2\text{-eq}}$. The used methods are part of the Environmental Footprint (EF) method family, which is the recommended impact assessment method family of the European Union (Fazio et al., 2018).

Future research shall explore how the investigated materials contribute to non-climate-change related environmental impacts, such as abiotic resource depletion and acidification potential, PM2.5, among other impact indicators. However, the focus and scope of this study has focused solely on the impact of climate change, this approach is justified by the assumption that if a material does not exhibit favourable characteristics in terms of GHG emissions, its market viability is compromised from the outset. Therefore, this study is the first investigation to assess its environmental footprint and subsequently study its feasibility.

3.4. Results

3.4.1. Current impact

Table 3 shows the results for cements, cement pastes and mortar for the year 2020, the starting year of the study. The slightly different values between SSP2-Base and SSP2-RCP1.9 can be explained by small modifications to the background electricity mix that have already been modelled in 2020 based on REMIND. The impact of mortars is lower compared to cement or cement pastes due to the different proportions and material dosages employed.

Table 4 shows the impacts on climate change for all scenarios considered for each material and functional unit evaluated.

3.4.2. Electricity scenario

Fig. 7 shows the climate change results for the electricity scenario for the different cements. In these scenarios, the electricity supply throughout the production processes of the cements has been replaced with the future projected electricity mix from the IAM REMIND. The electricity consumed in the mixing process of the three evaluated materials has been assumed to be uniform. It is shown that the environmental impact is lower when using MPC-TUN compared to the other materials for all cement applications studied: cement,

Table 3
Current impact in the year 2020.

		Climate change	
		kg $CO_{2-eq.}$	
		SSP2-Base	SSP2-RCP1.9
		2020	2020
Cement [tonne]	OPC-CEM I	830	820
	MPC-MgO	1160	1130
	MPC-TUN	430	420
Cement paste [m³]	OPC-CEM I	1197	1186
	MPC-MgO	1478	1441
	MPC-TUN	657	632
Mortar [m³]	OPC-CEM I	363	361
	MPC-MgO	591	577
	MPC-TUN	275	266

Table 4
Impacts of the different scenarios evaluated in the pLCA.

		Electricity scenario				Fuel and electricity scenario			
		Climate change							
		kg $CO_{2-eq.}$							
		SSP2-Base		SSP2-RCP1.9		SSP2-Base		SSP2-RCP1.9	
		2030	2050	2030	2050	2030	2050	2030	2050
Cement [tonne]	OPC-CEM I	820	810	810	810	760	700	750	700
	MPC-MgO	1100	1040	1000	960	1050	850	940	760
	MPC-TUN	400	370	350	330	370	290	320	250
Cement paste [m³]	OPC-CEM I	1187	1169	1165	1162	1103	1014	1078	1004
	MPC-MgO	1401	1316	1266	1217	1331	1077	1195	972
	MPC-TUN	609	554	524	495	566	434	480	372
Mortar [m³]	OPC-CEM I	361	356	354	353	339	316	332	313
	MPC-MgO	562	531	513	495	537	445	487	406
	MPC-TUN	259	240	230	220	245	201	216	180

cement paste and mortar. Conversely, MPC-MgO stands out as the material with the greatest environmental impact, higher than OPC. For OPC, the climate change impact stays almost constant over time despite a continuously cleaner electricity mix. This shows that electricity is only a minor driver for climate change for OPC, for which most impact stems from calcination and fuel combustion.

Concerning the development over time in the electricity scenario, more impact reduction is achieved, as expected, in the 1.5C-compliant scenario (SSP2-RCP1.9) than in the business as usual (SSP2-Base), which, however, also shows modest reductions. Focusing on the mortars in the SSP2-Base pathways in 2050, the following observations can be made for their climate change impact (Fig. 8).

i) Clinker production is responsible for 82.8% of the impact of OPC-CEM I mortar.
ii) For the MPC-MgO mortar, MKP production causes 60.2% of the impact, while 20.5% comes from MgO production. Additionally, 8.7% of the impact comes from the calcination process of magnesite, which is crucial for achieving the desired reactivity required for its use as a raw material.

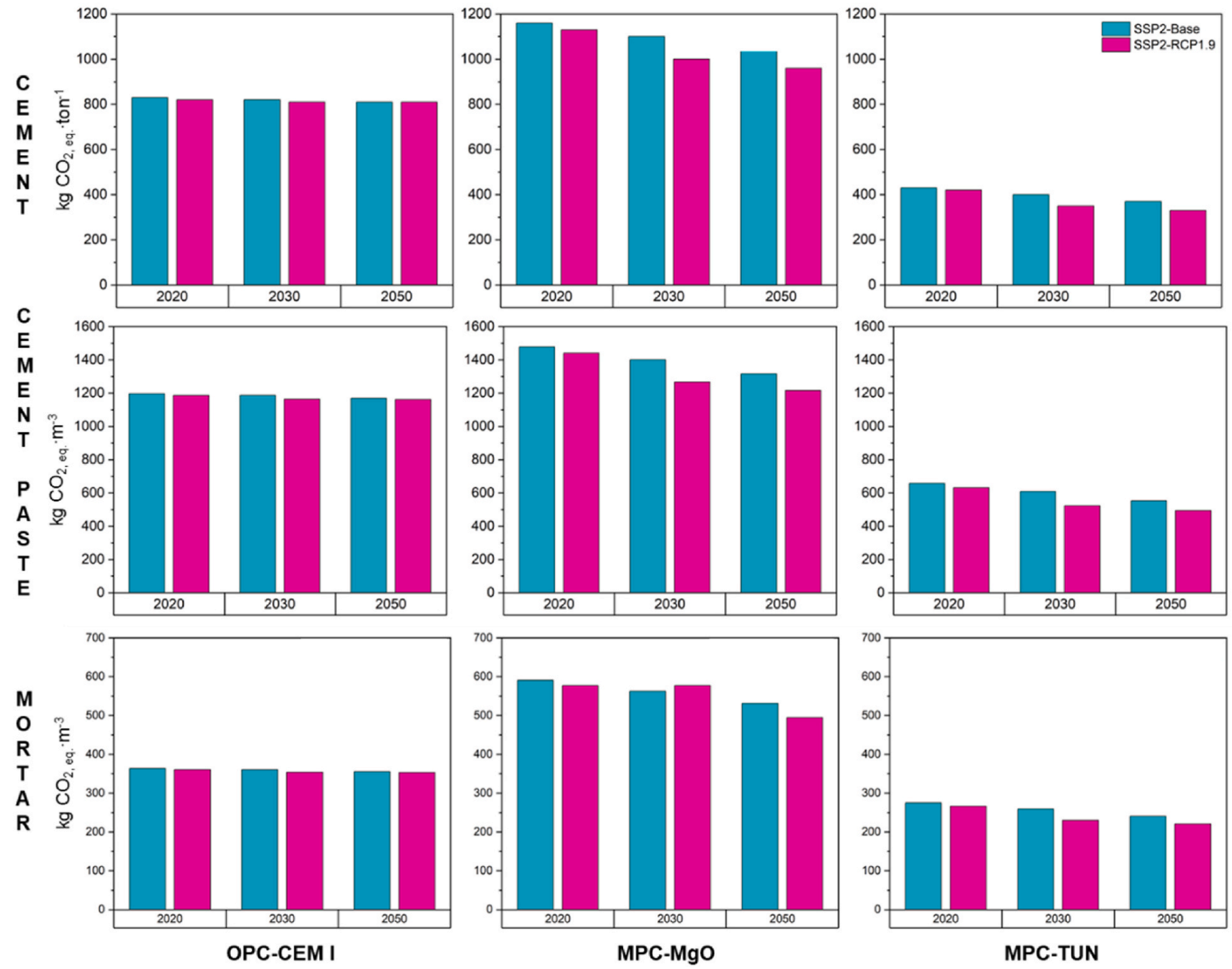

Fig. 7. Results for climate change category for electricity scenario.

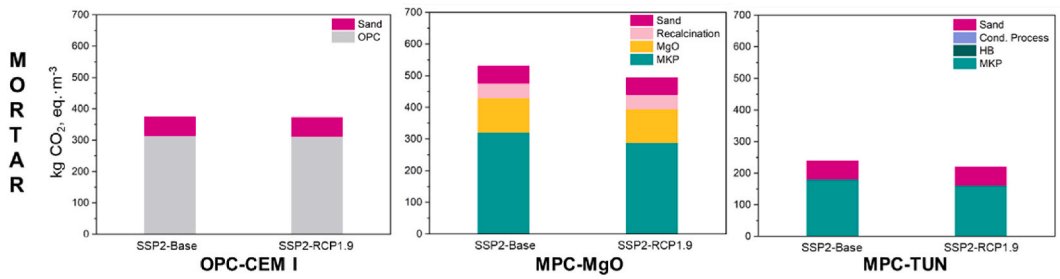

Fig. 8. Contributions of mortars to climate change impacts for the electricity scenario in the year 2050 (OPC, Ordinary Portland Cement; MgO, magnesium oxide; MKP, monopotassium phosphate; Cond. Process, conditioning process; HB, boric acid).

iii) For MPC-TUN mortar, MKP causes 73.5% of the impact. More precisely, 35.7% is attributed to phosphoric acid, and 37.8% to potassium hydroxide. Additionally, 1.2% of the impact is attributed to HB, while 0.4% is associated with the TUN conditioning process.

Moving forward to the SSP2-RCP1.9 pathway for the same year 2050, the following slight changes in impacts for the mortars can be observed.

i) For the OPC-CEM I mortar, 83% of the impact still comes from the production of clinker.

ii) For the MPC-MgO, 58% of the impact originates from MKP, 21.5% from MgO production, and 9.3% from the recalcination of magnesite to obtain the desired reactivity.
iii) For the MPC-TUN mortar, MKP causes 71.8% of the impact, HB 1.2%, and 0.1% stems from the TUN conditioning process.

It is crucial to highlight that the remaining impact on climate change of each material is associated with the use of silica sand (Fig. 8). These assessments provide valuable insights into the climate change impacts of the different mortars under consideration for the specified scenarios. First and foremost, it can be deduced from the different pathways evaluated that for the OPC-CEM I mortar, the impact comes mainly from the clinker. In the case of MPC-MgO, the production of DBM incurs a significant energy consumption and leads high CO_2 emissions, while the production of MKP is also a significant contributor. Lastly, in the context of MPCs, the MKP component stands out as having the most significant impact. The percentage shift in the impact contribution of MKP between MPC-MgO and MPC-TUN can be attributed to variations in their respective compositions.

Moreover, it is noticeable that in the future the different impacts are decreasing. This trend can be attributed to the continuous reduction in fossil-fuel based electricity generation in both scenarios. Besides, the impacts of SSP2-RCP1.9 are lower compared to SSP2-Base, as can be seen in Fig. 7. This difference could be because SSP2-RCP1.9 incorporates a faster phase-out of fossil-based electricity and higher shares of low-carbon energy sources to achieve the goals outlined in the Paris Agreement.

Finally, considering SSP2-RCP1.9 pathway and looking forward to the year 2050, it can anticipate the following mortar related changes. Specifically, MPC-TUN exhibits a 38% reduction in climate change impacts compared to OPC-CEM I and a 55% reduction in impacts compared to MPC-MgO mortar.

3.4.3. Fuel and electricity scenario

The trends of the combined scenario are consistent with the electricity-only scenario, but reductions over time are more pronounced. MPC-TUN shows the smallest footprint concerning the climate change impact category, followed by OPC-CEM I and MPC-MgO, as shown in Fig. 9.

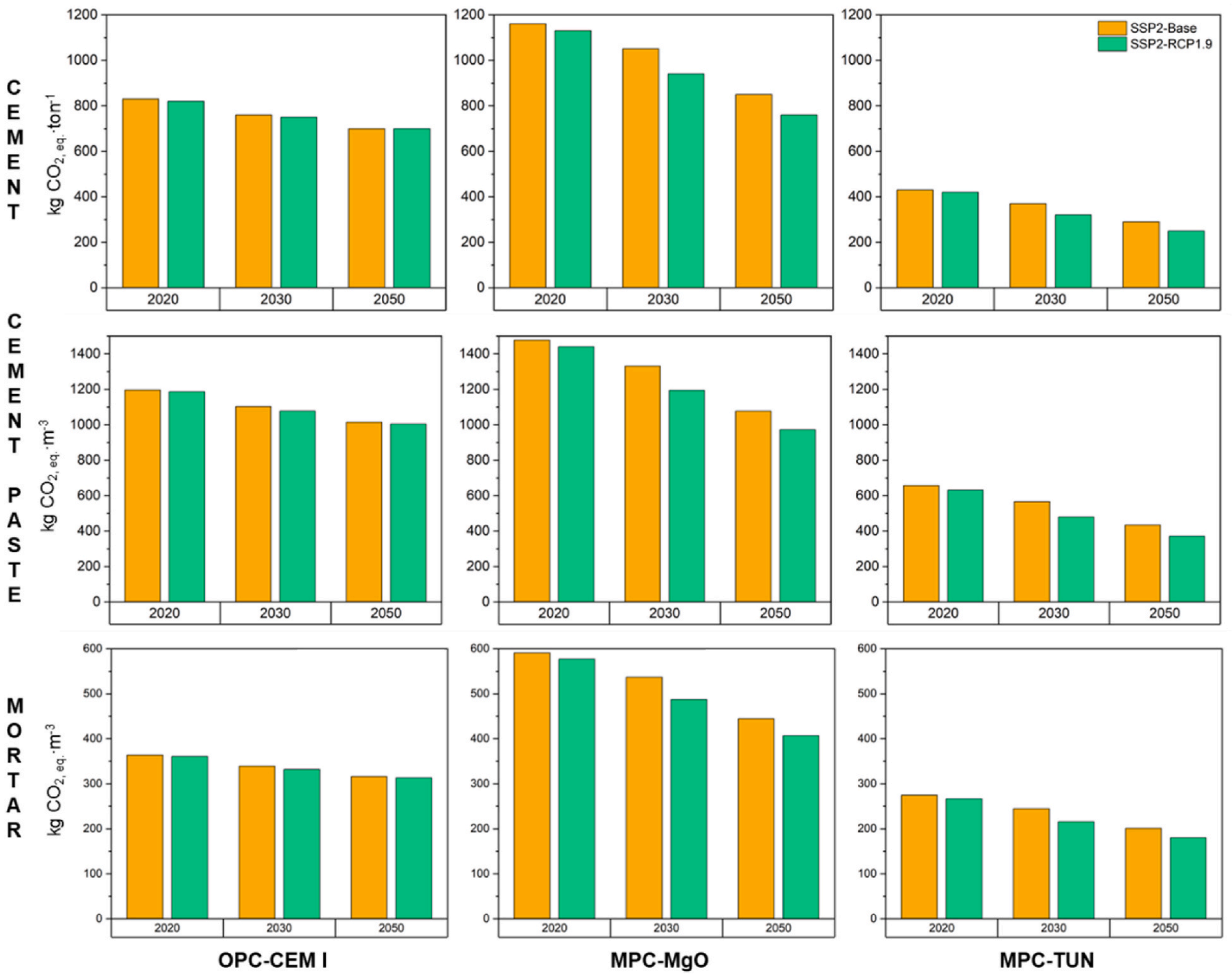

Fig. 9. Climate change category for electricity and fuel scenario.

Fig. 10 shows the environmental contributions of mortars for each material in the SSP2-Base and SSP2-RCP1.9 scenarios for 2050, considering future assumptions. The additional implementation of a cleaner fuel mix in cement production reduces the overall emissions compared to those of the previous scenario, which only included electricity decarbonisation. Nevertheless, it is noteworthy that the distribution of impact contributions remains similar to that of the previous scenario, as the primary contributors for each type of mortar remain consistent.

In the SSP2-RCP1.9 scenario, the $CO_{2\text{-eq}}$ emissions (Fig. 9) of the combined scenarios (electricity and fuel) display a decreasing trend for all mortars over the years.

i) For the OPC-CEM I, emissions are decreased from 361 kg CO_2 eq. in 2020 to 313 kg CO_2 eq. in 2050 (reduction of ≈13%).
ii) For the MPC-MgO, emissions descend from 577 kg CO_2 eq. in 2020 to 406 kg CO_2 eq. in 2050 (reduction of ≈30%).
iii) For the MPC-TUN, emissions fall from 266 kg CO_2 eq. in 2020 to 180 kg CO_2 eq. in 2050 (reduction of ≈32%).

A particularly significant aspect of this scenario lies in the notable decrease in impacts when compared to the previous scenario. In the context of mortars focusing on the fuel and electricity scenario for SSP2-RCP1.9 by 2050, there is a significant reduction compared to electricity scenario: 13% for OPC-CEM I, 22% for MPC-MgO, and 22% for MPC-TUN. This emphasizes the pivotal role that fuel sources play across various sectors and underscores their profound influence on environmental impact. Lastly, looking ahead to the year 2050 for the SSP2-RCP1.9 pathway, MPC-TUN causes 42% less climate change impacts than OPC-CEM I and 56% less impacts compared to MPC-MgO.

An assessment of emerging materials, despite their current low rate of application and the challenges they face to achieve industrial production, is significant as it describes their potential for climate change mitigation. However, these evaluations incorporate the scale-up of production at the industrial level of production, the study of the properties at the laboratory level so that they have the same applicability as commercial products, among others.

4. Discussion

The impact of climate change on society and the conservation of the natural world are intertwined; thus, it is impossible to resolve one without addressing the other. The LCA methodology is increasingly gaining more importance in the construction sector, as it allows to evaluate the environmental impacts associated with the materials or processes evaluated (AzariJafari et al., 2021; Jiang et al., 2023; Martínez-Rocamora et al., 2016).

4.1. Materials

This study adopts the LCA method to assess the climate change of using different types of cements in the construction sector as non-structural precast elements. The results show that the cement industry can reduce its emissions by adopting low-carbon cements, such as MPC-TUN, but also by considering low-carbon electricity and fuels. The results underscore the importance of utilizing recovered materials, such as MPC-TUN, instead of relying solely on pure materials or on by-products. By incorporating waste materials, the environmental impacts associated with sending materials to landfills and virgin resource extraction can be avoided. This can contribute both to climate change mitigation and a more circular economy (European Commission. Joint Research Centre. Institute for Environment and Sustainability, 2010). However, one must be aware of the limitations and uncertainty of this material, as it is currently at laboratory scale (TLR 3). Therefore, hypotheses have been made concerning its viability as a commercial product and its energy requirements during manufacture.

The results show that the MPC-TUN materials display the lowest CO_2 emissions score in all applications studied as they avoid calcination related GHG emissions. Thus, a climate benefit is observed for this novel material. Additionally, in all scenarios, it is evident that MPC-TUN demonstrates a reduced impact compared to MPC-MgO. This reduction can be attributed to the use of a waste as a source of MgO instead of using pure MgO, which contains substantial amounts of fossil fuel resources and CO_2 emissions in its supply chain.

However, the presence of MKP in all MPCs presents another significant environmental challenge. To ensure a sustainable development, it is essential to explore ways to reduce emissions associated with MKP production or find alternative sources for obtaining this material. The search for different residual sources or more environmental methods to obtain MKP is crucial to further enhance the sustainability of MPC-based mortars.

Focusing on the OPC-CEM I, main efforts in the upcoming years include to replace and reduce clinker usage, which are integral steps of the roadmap for the cement industry. The reduction of clinker content helps mitigate the carbon footprint associated with OPC production.

4.2. Scenarios

The electricity scenario has shown how an increasingly decarbonized electricity system reduces the climate change impact of the assessed materials for the same applicability. Here, a higher reduction is observed for the MPC-based materials than the OPC-cement based ones and a higher reduction in the more climate-ambitious scenario SSP2-RCP1.9 compared to the baseline scenario (SSP2-Base). The combined scenarios of electricity and fuel sector show the additional savings that can be achieved from a changing thermal fuel market in the upcoming years: the values obtained in the electricity and fuel scenario, as shown in Fig. 9, are better compared to the electricity-only scenario (Fig. 7). This improvement is based on the change in the fuel oil market (shift from coal to biomass and bio propane). Also, in the combined scenarios, which implement the same future heat mixes in both pathways, the deeper decarbonisation of the electricity mix in the SSP2-RCP1.9 pathway results in larger impact reductions compared to the SSP2-Base pathway.

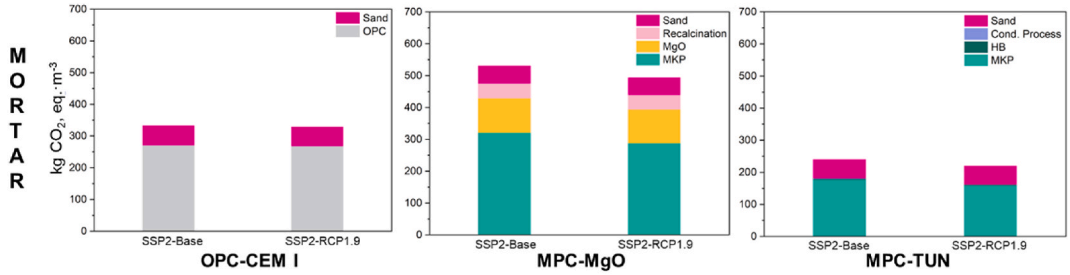

Fig. 10. Contributions of mortars to climate change impacts for the electricity and fuel scenario (OPC, Ordinary Portland Cement; MgO, magnesium oxide; MKP, monopotassium phosphate; Cond. Process, conditioning process; HB, boric acid).

The scenario assessment highlights the significant role played by the construction sector. The extent to which the projected more sustainable electricity and fuel supply can be achieved depends on the political frameworks, infrastructures development, and economic factors. This necessitates detailed studies to evaluate their viability and enhance facilities in terms of energy storage, demand response, network extension, and renewable sources (de Brito and Kurda, 2021; Munaro and Tavares, 2023; Scrivener et al., 2019; Wang et al., 2023). However, in a future study it would be of great interest to also introduce enhancements in efficiency, technological advancements, and other factors in cement production in the future projections. These projections would be related to a reduction in the assessed impacts.

Finally, this study demonstrates that the introduction of MPC-TUN aligns with the construction sector's roadmap in terms of exploring alternative materials. Then, it should be noted that.

- To allow the incorporation of different cements, it will be essential to have the regulations in place that guarantee their properties.
- The cement industry has several actions it can take to reduce the emissions, introduce low-carbon technologies, and embrace circularity. It is crucial to emphasize that this sector requires political and funding support to achieve the environmental goals since it cannot reach them on its own.

5. Conclusions

This study shows that all MPC-TUN materials demonstrate a significant reduction in climate change impacts compared their OPC-CEM I and MPC-MgO-based alternatives in all scenarios. Therefore, MPC-TUN is shown to be a more climate friendly cement type that simultaneously contributes to waste prevention, raw materials reduction, and a more circular economy by utilizing waste from the steel industry. Our results also show that MPC-MgO based materials have the highest impact on climate change, higher than OPC-CEM I. This highlights the fact that not all alternatives to clinker-based Portland cements necessarily result in a benefit for the climate. When assessing these findings, it is crucial to acknowledge that the MPC-TUN has not been developed for industrial use yet but is currently at laboratory scale (TLR3). This means that there are significant uncertainties concerning production parameters when upscaling MPC-TUN to industrial use, such as conditioning process. Nonetheless, efforts have been made to minimize the uncertainty by estimating the performance this process.

The scenario analysis in this study highlights the potential impact reductions over time that arise from using a decarbonized future electricity mix and greener thermal heat supply. This points to the significant reduction potential for the cement industry by switching to greener electricity and fuels, next to adopting low-carbon alternative cements, such as MPC-TUN.

To reduce the energy demand and climate change impact of MPC-TUN materials further, it will be necessary to seek new sources of MKP from residual and alternative sources. Simultaneously, this approach promotes the circular economy by utilizing waste as raw materials, thereby avoiding the need to send it to landfills. Moreover, utilizing these alternative sources of phosphate could significantly help in lowering the final cost of the product. As MPC-TUN is still at laboratory scale, it is essential to implement new regulations, do more research, and secure financial support to mature this novel, climate-friendlier construction material and overcome its barriers to adoption. For their future applicability as construction material, MPC-TUN must be thoroughly evaluated to verify technical requirements, including durability in different environments and the achievement of optimal mechanical properties, among other specifications.

CRediT authorship contribution statement

Anna Alfocea-Roig: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Amelie Müller:** Writing – review & editing, Supervision, Software, Resources, Methodology. **Bernhard Steubing:** Writing – review & editing, Supervision, Resources, Methodology. **Sergio Huete-Hernández:** Writing – review & editing, Resources. **Jessica Giro-Paloma:** Writing – review & editing, Visualization, Supervision, Conceptualization. **Joan Formosa:** Writing – review & editing, Visualization, Supervision, Funding acquisition, Conceptualization.

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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

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scp.2024.101802.

References

Agrupación de fabricantes de cemento de España, 2021. Hoja de ruta de la industria cementera española para alcanzar la neutralidad climática en 2050. Oficemen.
Aguirre-Villegas, H.A., Milani, F.X., Kraatz, S., Reinemann, D.J., 2012. Life cycle impact assessment and allocation methods development for cheese and whey processing. Trans. ASABE (Am. Soc. Agric. Biol. Eng.) 55, 613–627. https://doi.org/10.13031/2013.41363.
Alfocea-Roig, A., Huete-Hernández, S., García-Zubiri, X., Giro-Paloma, J., Formosa, J., 2023. Can tundish deskulling waste be used as a magnesium oxide source to develop magnesium phosphate cement? J. Environ. Chem. Eng. 11. https://doi.org/10.1016/j.jece.2023.110618.
Amanatidis, G., 2019. European Policies on Climate and Energy towards 2020, 2030 and 2050.
An, J., Li, Y., Middleton, R.S., 2018. Reducing energy consumption and carbon emissions of magnesia refractory products: a life-cycle perspective. J. Clean. Prod. 182, 363–371. https://doi.org/10.1016/j.jclepro.2018.01.266.
Anna Nilsson, F.H., Legarreta, P.L., Lui, S., Röser, F., 2020. Decarbonisation Pathways for the EU Cement Sector: Technology Routes and Potential Ways Forward. New Climate Institute.
Arvidsson, R., Tillman, A.M., Sandén, B.A., Janssen, M., Nordelöf, A., Kushnir, D., Molander, S., 2018. Environmental assessment of emerging technologies: recommendations for prospective LCA. J. Ind. Ecol. https://doi.org/10.1111/jiec.12690.
AzariJafari, H., Guest, G., Kirchain, R., Gregory, J., Amor, B., 2021. Towards comparable environmental product declarations of construction materials: insights from a probabilistic comparative LCA approach. Build. Environ. 190. https://doi.org/10.1016/j.buildenv.2020.107542.
Batuecas, E., Ramón-Álvarez, I., Sánchez-Delgado, S., Torres-Carrasco, M., 2021. Carbon footprint and water use of alkali-activated and hybrid cement mortars. J. Clean. Prod. 319. https://doi.org/10.1016/j.jclepro.2021.128653.
Brugger, H., Eichhammer, W., Mikova, N., 2021. Energy Efficiency Vision 2050: how will new societal trends influence future energy demand in the European countries? Energy Pol. 152.
Castillo, V.Z., Boer, H.S. de, Muñoz, R.M., Gernaat, D.E.H.J., Benders, R., van Vuuren, D., 2022. Future global electricity demand load curves. Energy 258. https://doi.org/10.1016/j.energy.2022.124741.
CEMBUREAU, 2021. Reaching Climate Neutrality along the Cement and Concrete Value Chain by 2050. Cementing the European Green Deal.
de Brito, J., Kurda, R., 2021. The past and future of sustainable concrete: a critical review and new strategies on cement-based materials. J. Clean. Prod. 281. https://doi.org/10.1016/j.jclepro.2020.123558.
Eberhardt, L.C.M., van Stijn, A., Rasmussen, F.N., Birkved, M., Birgisdottir, H., 2020. Development of a life cycle assessment allocation approach for circular economy in the built environment. Sustainability 12, 1–16. https://doi.org/10.3390/su12229579.
El-Dieb, A.S., Kanaan, D.M., 2018. Ceramic waste powder an alternative cement replacement – characterization and evaluation. Sustainable Materials and Technologies 17. https://doi.org/10.1016/j.susmat.2018.e00063.
Ellis Gartner A, T.S.B., 2018. Alternative cement clinkers. Cement Concr. Res. 114, 27–39. https://doi.org/10.1016/j.cemconres.2017.02.002.
European Commission. Joint Research Centre. Institute for Environment and Sustainability, 2010. Framework and Requirements for Life Cycle Impact Assessment Models and Indicators. Publications Office.
Fazio, S., Biganzioli, F., De Laurentiis, V., Zampori, L., Sala, S., Diaconu, E., 2018. Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment methods, version 2, from ILCD to EF 3.0. New Models and Differences with ILCD, EUR. https://doi.org/10.2760/002447.
Folliet, Michel, Milagros Rivas Saiz, J.S., 2017. Improving thermal and electric energy efficiency at cement plants. Improving Thermal and Electric Energy Efficiency at Cement Plants. https://doi.org/10.1596/28304.
Font, A., Soriano, L., de Moraes Pinheiro, S.M., Tashima, M.M., Monzó, J., Borrachero, M.V., Payá, J., 2020. Design and properties of 100% waste-based ternary alkali-activated mortars: blast furnace slag, olive-stone biomass ash and rice husk ash. J. Clean. Prod. 243. https://doi.org/10.1016/j.jclepro.2019.118568.
Formosa, J., Chimenos, J.M., Lacasta, A.M., Niubó, M., 2012. Interaction between low-grade magnesium oxide and boric acid in chemically bonded phosphate ceramics formulation. Ceram. Int. 38, 2483–2493. https://doi.org/10.1016/j.ceramint.2011.11.017.
Georgiades, M., Shah, I.H., Steubing, B., Cheeseman, C., Myers, R.J., 2023. Prospective life cycle assessment of European cement production. Resour. Conserv. Recycl. 194. https://doi.org/10.1016/j.resconrec.2023.106998.

Giro-Paloma, J., Mañosa, J., Maldonado-Alameda, A., Quina, M.J., Chimenos, J.M., 2019. Rapid sintering of weathered municipal solid waste incinerator bottom ash and rice husk for lightweight aggregate manufacturing and product properties. J. Clean. Prod. 232, 713–721. https://doi.org/10.1016/j.jclepro.2019.06.010.

Gong, X., Nie, Z., Wang, Z., Cui, S., Gao, F., Zuo, T., 2012. Life cycle energy consumption and carbon dioxide emission of residential building designs in Beijing: A comparative study. Journal of Industry Ecology 16, 576–587. https://doi.org/10.1111/j.1530-9290.2011.00415.x.

Griffiths, S., Sovacool, B.K., Furszyfer Del Rio, D.D., Foley, A.M., Bazilian, M.D., Kim, J., Uratani, J.M., 2023. Decarbonizing the cement and concrete industry: a systematic review of socio-technical systems, technological innovations, and policy options. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2023.113291.

Guo, Y., Luo, L., Liu, T., Hao, L., Li, Y., Liu, P., Zhu, T., 2024. A review of low-carbon technologies and projects for the global cement industry. J. Environ. Sci. (China). https://doi.org/10.1016/j.jes.2023.01.021.

Heijungs, R., Guinée, J.B., 2007. Allocation and "what-if" scenarios in life cycle assessment of waste management systems. Waste Manag. 27, 997–1005. https://doi.org/10.1016/j.wasman.2007.02.013.

Hossain, M.U., Poon, C.S., 2018. Comparative LCA of wood waste management strategies generated from building construction activities. J. Clean. Prod. 177, 387–397. https://doi.org/10.1016/j.jclepro.2017.12.233.

How 'Shared Socioeconomic Pathways, 2018. explore future climate change. URL. https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change/.

Huete-Hernández, S., Maldonado-Alameda, A., Giro-Paloma, J., Chimenos, J.M., Formosa, J., 2021. Fabrication of sustainable magnesium phosphate cement micromortar using design of experiments statistical modelling: valorization of ceramic-stone-porcelain containing waste as filler. Ceram. Int. 47, 10905–10917. https://doi.org/10.1016/j.ceramint.2020.12.210.

International Energy Agency, 2021. World Energy Outlook 2021.

International Energy Agency, 2023. Technology Roadmap - Low-Carbon Transition in the Cement Industry.

Jiang, J., Chu, C., Song, L., Gao, X., Huang, B., Zhang, Yufei, Zhang, Yi, Liu, Y., Hou, L., Ju, M., Cao, Z., 2023. From prospecting to mining: a review of enabling technologies, LCAs, and LCCAs for improved construction and demolition waste management. Waste Manag. https://doi.org/10.1016/j.wasman.2023.01.017.

Kermeli, K., Edelenbosch, O.Y., Crijns-Graus, W., van Ruijven, B.J., Mima, S., van Vuuren, D.P., Worrell, E., 2019. The scope for better industry representation in long-term energy models: modeling the cement industry. Appl. Energy 240, 964–985. https://doi.org/10.1016/j.apenergy.2019.01.252.

Langkau, S., Steubing, B., Mutel, C., Permana, M., Lorenz, A., 2023. A stepwise approach for scenario - based inventory modelling for prospective LCA (SIMPL). Int. J. Life Cycle Assess. https://doi.org/10.1007/s11367-023-02175-9.

Luong, V.T., Amal, R., Scott, J.A., Ehrenberger, S., Tran, T., 2018. A comparison of carbon footprints of magnesium oxide and magnesium hydroxide produced from conventional processes. J. Clean. Prod. 202, 1035–1044. https://doi.org/10.1016/j.jclepro.2018.08.225.

Ma, H., Xu, B., Liu, J., Pei, H., Li, Z., 2014. Effects of water content, magnesia-to-phosphate molar ratio and age on pore structure, strength and permeability of magnesium potassium phosphate cement paste. Mater. Des. 64, 497–502. https://doi.org/10.1016/j.matdes.2014.07.073.

Ma, W., Liu, T., Hao, J.L., Wu, W., Gu, X., 2023. Towards a circular economy for construction and demolition waste management in China: critical success factors. Sustainable Chemistry and Pharmacy 35. https://doi.org/10.1016/j.scp.2023.101226.

Maes, B., Sacchi, R., Steubing, B., Pizzol, M., Audenaert, A., Craeye, B., Buyle, M., 2023. Prospective consequential life cycle assessment: identifying the future marginal suppliers using integrated assessment models. Renew. Sustain. Energy Rev. 188. https://doi.org/10.1016/j.rser.2023.113830.

Maldonado-Alameda, A., Lacasta, A.M., Giro-Paloma, J., Chimenos, J.M., Haurie, L., Formosa, J., 2017. Magnesium phosphate cements formulated with low grade magnesium oxide incorporating phase change materials for thermal energy storage. Construct. Build. Mater. 155, 209–216. https://doi.org/10.1016/j.conbuildmat.2017.07.227.

Maldonado-Alameda, A., Formosa, J., Chimenos, J.M., Huete-Hernández, S., Giro-Paloma, J., 2018. Geopolymer development based on the CSP residue as unique precursor. In: WASCON 2018. 10th International Conference on the Environmental and Technical Implications of Construction with Alternative Materials. Tampere, Finland.

Martínez-Rocamora, A., Solís-Guzmán, J., Marrero, M., 2016. LCA databases focused on construction materials: a review. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2015.12.243.

Mathias, T., 2009. Master of Science Thesis Principles of Benchmarking Criteria for the European Magnesia. University of Leoben, Austria.

Meinshausen, M., Nicholls, Z.R.J., Lewis, J., Gidden, M.J., Vogel, E., Freund, M., Beyerle, U., Gessner, C., Nauels, A., Bauer, N., Canadell, J.G., Daniel, J.S., John, A., Krummel, P.B., Luderer, G., Meinshausen, N., 2020. The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. Geosci. Model Dev. (GMD) 3571–3605. https://doi.org/10.5194/gmd-13-3571-2020, 2020.

Mendoza Beltran, A., Cox, B., Mutel, C., van Vuuren, D.P., Font Vivanco, D., Deetman, S., Edelenbosch, O.Y., Guinée, J., Tukker, A., 2020. When the background matters: using scenarios from integrated assessment models in prospective life cycle assessment. Journal of Industry Ecology 24, 64–79. https://doi.org/10.1111/jiec.12825.

Meng, X., Jiang, Y., Chen, B., Wang, L., 2023. Research progress on the setting time and solidification mechanism of magnesium phosphate cement: a review. Construct. Build. Mater. https://doi.org/10.1016/j.conbuildmat.2023.133612.

Müller, A., Harpprecht, C., Sacchi, R., Maes, B., van Sluisveld, M., Daioglou, V., Šavija, B., Steubing, B., 2024. Decarbonizing the cement industry: findings from coupling prospective life cycle assessment of clinker with integrated assessment model scenarios. J. Clean. Prod. 450. https://doi.org/10.1016/j.jclepro.2024.141884.

Munaro, M.R., Tavares, S.F., 2023. A review on barriers, drivers, and stakeholders towards the circular economy: the construction sector perspective. Cleaner and Responsible Consumption 8. https://doi.org/10.1016/j.clrc.2023.100107.

Niewiadomski, P., Karolak, A., Stefaniuk, D., Królicka, A., Szymanowski, J., Sadowski, Ł., 2021. Cement paste mixture proportioning with particle packing theory: an ambiguous effect of microsilica. Materials 14. https://doi.org/10.3390/ma14226970.

Normalización Española, 2018. UNE-EN_196-1:2018 Methods of Testing Cement - Part 1. Determination of strength.

Panesar, D.K., Seto, K.E., Churchill, C.J., 2017. Impact of the selection of functional unit on the life cycle assessment of green concrete. Int. J. Life Cycle Assess. 22, 1969–1986. https://doi.org/10.1007/s11367-017-1284-0.

Potsdam Institute for climate impact research - premise. https://premise.readthedocs.io/en/latest/introduction.html, 2023 (accessed 5.25.23).

Pryshlakivsky, J., Searcy, C., 2013. Fifteen years of ISO 14040: a review. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2013.05.038.

Real, S., Bogas, J.A., Carriço, A., Hu, S., 2021. Mechanical characterisation and shrinkage of thermoactivated recycled cement concrete. Appl. Sci. 11. https://doi.org/10.3390/app11062454.

Remind. https://github.com/remindmodel/remind, 2023 (accessed 7.28.23).

Riahi, K., Vuuren, D.P. Van, Kriegler, E., Edmonds, J., Neill, B.C.O., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Crespo, J., Kc, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Aleluia, L., Silva, D., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Stre, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J.C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-campen, H., Obersteiner, M., Tabeau, A., Tavoni, M., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications. An overview 42, 153–168.

Ruan, S., Unluer, C., 2016. Comparative life cycle assessment of reactive MgO and Portland cement production. J. Clean. Prod. 137, 258–273. https://doi.org/10.1016/j.jclepro.2016.07.071.

Sacchi, R., Terlouw, T., Siala, K., Dirnaichner, A., Bauer, C., Cox, B., Mutel, C., Daioglou, V., Luderer, G., 2022. PRospective EnvironMental Impact asSEment (premise): a streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. Renew. Sustain. Energy Rev. 160. https://doi.org/10.1016/j.rser.2022.112311.

Scrivener, K., Habert, G., De Wolf, C.F.A., 2019. A Sustainable Future for the European Cement and Technology Assessment for Full Decarbonisation of the Industry by 2050.

Sinka, M., Van den Heede, P., De Belie, N., Bajare, D., Sahmenko, G., Korjakins, A., 2018. Comparative life cycle assessment of magnesium binders as an alternative for hemp concrete. Resour. Conserv. Recycl. 133, 288–299. https://doi.org/10.1016/j.resconrec.2018.02.024.

Sousa, V., Bogas, J.A., Real, S., Meireles, I., Carriço, A., 2023. Recycled cement production energy consumption optimization. Sustainable Chemistry and Pharmacy 32. https://doi.org/10.1016/j.scp.2023.101010.

Turk, J., Cotič, Z., Mladenovič, A., Šajna, A., 2015. Environmental evaluation of green concretes versus conventional concrete by means of LCA. Waste Manag. 45, 194–205. https://doi.org/10.1016/j.wasman.2015.06.035.

Valipour, M., Yekkalar, M., Shekarchi, M., Panahi, S., 2014. Environmental assessment of green concrete containing natural zeolite on the global warming index in marine environments. J. Clean. Prod. 65, 418–423. https://doi.org/10.1016/j.jclepro.2013.07.055.

Wang, Q., Xu, X., Liang, K., 2021. The impact of environmental regulation on firm performance: evidence from the Chinese cement industry. J. Environ. Manag. 299. https://doi.org/10.1016/j.jenvman.2021.113596.

Wang, N., Xu, Z., Liu, Z., 2023. Innovation in the construction sector: bibliometric analysis and research agenda. Journal of Engineering and Technology Management - JET-M 68. https://doi.org/10.1016/j.jengtecman.2023.101747.