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Life cycle assessment of clinker and cement production in Spain. Environmental assessment of decarbonisation measures

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ABSTRACT

This study examines the environmental impacts of clinker and cement production in Spain, focusing on the effects of current practices and future decarbonisation strategies through a cradle-to-gate life cycle assessment (LCA). Three scenarios were analysed: the baseline scenario, which uses global statistical data on the production and consumption of raw materials and energy in Spain in 2021, and two future scenarios for 2030 and 2050. The impact of implementing various decarbonisation measures proposed in the Spanish cement sector roadmap was evaluated and analysed in the future scenarios. These measures primarily include substituting fossil fuels with biomass- and waste-derived fuels, improving thermal efficiency, and reducing the clinker-to-cement ratio. The results showed that, in six out of the eleven environmental impact categories assessed, impacts were reduced, while increases were observed in the remaining five categories. Global Warming Potential stands out among the categories with reduced impacts, with reductions of 18 % and 36 % projected for cement production in 2030 and 2050, respectively. On the other hand, the categories that showed increased impacts are mainly associated with the greater use of biomass-derived fuels, suggesting the convenience of further exploring their potential implications on the sector's overall environmental performance.

1. Introduction

Cement is a significant basic material for concrete manufacturing in the construction sector. It serves as a binder for the aggregates that enter into concrete composition (IEA, 2018; Marmier, 2023). Cement is produced by grinding clinker, gypsum, and additives. Clinker, the intermediate product in cement manufacturing, is the primary source of its environmental impacts. Clinker is made by crushing, mixing, and grinding limestone with clay and sand to form the raw meal, which is then heated in a kiln to 1,450 °C. At 900 °C, calcium carbonate ($CaCO_3$) decomposes into calcium oxide (CaO), releasing carbon dioxide (CO_2). The CaO is then sintered with silica, alumina, and iron oxides at 1,450 °C to form clinker (Marmier, 2023). Global demand for concrete, and thus cement, is currently driven by a growing population and rising affluence, coupled with urbanisation, especially in upper-middle-income Asian countries (UNEP, 2024).

Global production was estimated at approximately 4,300 million tonnes to supply this demand in 2021 (CEMBUREAU, 2023). Around 9 % of the world's production was produced in Europe. Spain is a key player in the European cement sector, ranking fifth in the EU27 producer with 16.2 Mt of cement in 2021, though still below pre-2008 levels (Marmier, 2023; Oficemen, 2022b; USGS, 2009). Clinker and cement production in Spain is spread throughout the country, mainly clinker and grey cement production. A map showing the distribution of cement plants in Spain and a detailed analysis of the Spanish production, based on information provided by the Spanish Cement Manufacturers Association

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(OFICEMEN) (Oficemen, 2022b, 2023), can be found in Appendix A.

Cement is widely recognised as an energy- and emission-intensive industry, responsible for 7 % of industrial energy use and responsible for 7-8 % of global CO_2 emissions (Marmier, 2023). This environmental impact underscores the need for decarbonisation measures to support Sustainable Development Goals 11, 12, and 13 (UN, 2015).

The clinker kiln is the main pollution hotspot in cement production due to its impact on climate change (García-Gusano et al., 2015). Clinker, which provides cement's strength, represented around 80 % of cement in 2021, though this varies (Marmier, 2023). The industry also emits carbon monoxide (CO), nitrogen oxides (NOx), dust/particulate matter (PM), sulphur oxides (SOx), and volatile organic compounds (VOC) (Çankaya, 2020; García-Gusano et al., 2015).

Life Cycle Assessment (LCA) is widely used to evaluate the environmental impacts of cement production globally. In Europe, Georgiades et al. (2023) projected climate change impacts up to 2050 under various decarbonisation scenarios. In Spain, García-Gusano et al. (2015) focused on Global Warming Potential using 2010 data, and like Valderrama et al. (2013), both examined decarbonisation measures. Moretti and Caro (2017) assessed process-stage impacts from 11 factories in Italy. In Germany, Feiz et al. (2015) studied decarbonisation strategies. Georgiopoulou and Lyberatos (2018) and Mathioudakis et al. (2021) explored fossil fuel substitution in Greece. Outside Europe, Kajaste & Hurme (2016) conducted a global study linking GHG emission management in cement production to clinker substitutes, energy sources, electricity emissions, technology, and geography. In China, Chen et al. (2015) analysed emissions using local and national data, while Liang et al. (2023) focused on municipal waste as fuel. Meshram & Kumar (2022) studied geopolymer cement as a Portland alternative in India. In Myanmar, several studies (Thwe et al., 2021; Tun et al., 2020, 2021) examined impacts and decarbonisation measures. Similar efforts were made in Turkey (Çankaya and Pekey, 2019), Tunisia (Cherni et al., 2024), Ethiopia (Wolde et al., 2024), Cuba (Sánchez Berriel et al., 2016) and Ecuador (Petroche and Ramirez, 2022).

Scientific literature shows growing interest in using LCA to evaluate measures that reduce the environmental impact of clinker and cement production. Georgiades et al. (2023) projected climate impacts in Europe up to 2050 under scenarios involving clinker substitution, alternative fuels, kiln upgrades, carbon capture, and energy mix decarbonisation. Fossil fuel substitution has been studied using waste oils and refuse-derived fuels (Çankaya and Pekey, 2019), full coal replacement with natural gas (Thwe et al., 2021), and alternatives like refuse-derived fuels, tire-derived fuels, biological sludge (Georgiopoulou and Lyberatos, 2018), and food waste (Mathioudakis et al., 2021). Valderrama et al. (2013) found that substituting fossil fuels and raw materials with sewage sludge improved environmental performance. These studies report CO_2 reductions with increasing biomass fuel use. LCA-based studies also address clinker content reduction: Feiz et al. (2015) examined blast furnace slag substitution; Sánchez Berriel et al. (2016) emphasized the benefits of LC3 cement; and Kajaste and Hurme (2016) identified lower clinker ratios as a key mitigation strategy. Terán-Cuadrado et al. (2024) noted that supplementary cementitious materials reduce GWP but may raise other impacts. Meshram & Kumar (2022) analysed geopolymer cement as a promising alternative to Portland. Müller et al. (2024) projected global clinker production impacts to 2060 under various climate scenarios, finding CO_2 reductions alongside increases in other environmental impacts.

Recent studies on CO_2 capture technologies in cement production have highlighted post-combustion methods like amine absorption, calcium looping, and membrane separation. Galusnyak et al. (2022) found calcium looping to be the most effective, although it reduced some environmental impacts while increasing others. Furthermore, a study including oxyfuel technology in its analysis also supported calcium looping's superiority over other methods (Bacatelo et al., 2023).

The literature review reveals that the impacts of clinker and cement production were previously studied in various countries using specific factory data. Often, various decarbonisation strategies were then evaluated. However, no studies have been found that evaluate the environmental impacts of clinker and cement production in Spain in detail since García-Gusano et al. (2015) who used data from 2010. Using contemporary data is necessary to propose decarbonisation measures adapted to the evolution of the Spanish cement sector in the last decade or so.

Therefore, this research aims to carry out an environmental assessment through LCA of clinker and cement production in Spain using production data for the year 2021 (Oficemen, 2022b) – the most updated complete data available at the beginning of this research – evaluating 11 impact categories, and analysing the effect of the decarbonisation measures applied so far. Scenarios for 2030 and 2050 will also be projected following the Spanish roadmaps (Oficemen, 2020a), increasing the use of alternative fuels derived from waste and biomass in kilns, and reducing the proportion of clinker in cement by adding supplementary cementitious materials.

2. Methodology

This article evaluates the environmental impact of Spain's total clinker and cement production in 2021 using Life Cycle Assessment (LCA). LCA is a scientifically recognised methodology that follows the ISO 14040 and 14044 standards (ISO, 2006b, 2006a), assessing all environmental aspects throughout a product's life cycle. This begins with the extraction of raw materials and extends through the manufacturing and usage phases, concluding with waste management. LCA comprises four distinct stages: (1) Goal and Scope, which establishes the functional unit and system boundaries; (2) Inventory Analysis, where inputs and outputs are catalogued and examined; (3) Impact Assessment, which transforms inventory data into potential environmental impacts; and (4) Interpretation, which is made for all the previous steps and specially for the verification of life cycle inventory and life cycle impacts results to draw conclusions in accordance with the goal and scope.

The LCAs in this study were conducted using SimaPro 9.5.1 software (PRé Sustainability, 2023) and the Ecoinvent 3.8 European database (Wernet et al., 2016). Specifically, the APOS v3 version of the Ecoinvent 3.8 database was selected for analysis.

2.1. *Goal, scope, data sources and tools*

This study aims to assess the environmental impact of clinker and cement production in Spain during 2021. For this purpose, two LCAs will be conducted: one for clinker and another for a weighted average of the produced cement in Spain considering the annual production of each Spanish factory. As functional units, one tonne of clinker or one tonne of cement were selected, respectively. In terms of activities, the scope of this LCA is a cradle-to-gate analysis. It includes all processes from the extraction and transport of the raw materials and fuels to the end of the cement production processes up to the point where the final product (clinker or cement) is stored, and ready to be shipped to customers. System boundaries of the LCA are presented in Fig. 1.

The clinker production process has been divided into six main stages: incorporation of natural and alternative raw materials (raw materials), calcination of limestone and marl (calcination), use of fuels in the kiln (fuels use), electricity consumption, transportation, and infrastructure. Additionally, the impact of fuels is categorized into fossil fuels, alternative fossil fuels, partially biomass, and biomass. In cement manufacturing ten stages have been considered; in addition to the six stages corresponding to clinker production, the following stages are included: cement plant infrastructure, raw materials, electricity for grinding and transportation of cement raw materials. The target audience are scientists and sustainability professionals interested in the decarbonisation of the cement industry as well as policy makers.

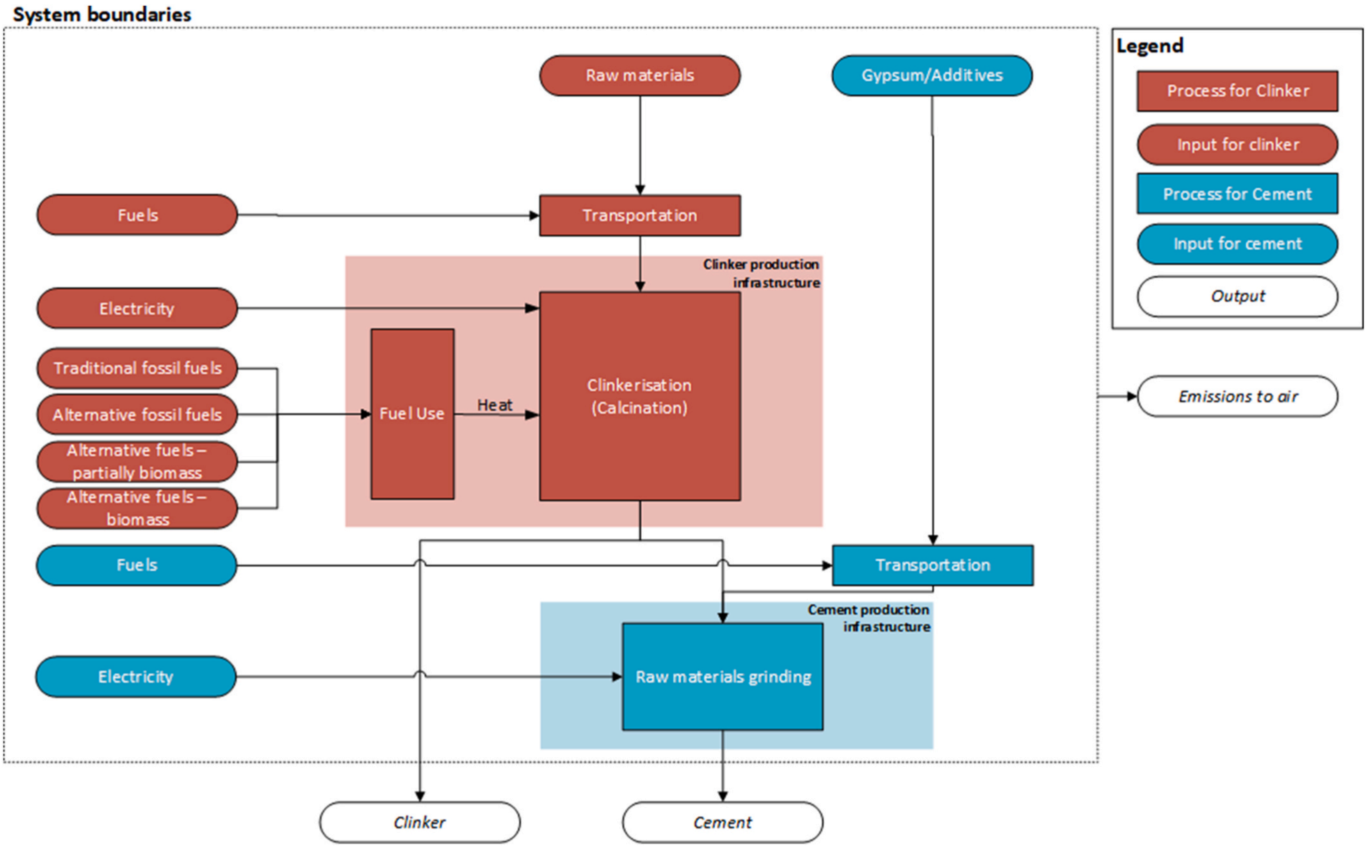

Fig. 1. System boundaries of the LCA.

2.2. *Life cycle inventory (LCI)*

LCI analysis involves data collection and system modelling per the defined scope. This study conducted two LCAs: one focused on clinker production and the other on average cement production for each analysed scenario. The approach covers the entire Spanish cement industry. Various scenarios were evaluated, with the 2021 baseline scenario mainly drawing data from the annual report on the Spain cement industry by Oficemen (2022b). The report provided comprehensive data on total production, including raw materials and energy consumption. Two future scenarios for 2030 and 2050 were proposed, assessing the impact of increasing the use of alternative fuels from waste and biomass in clinker production. Additionally, the reduction of the clinker-to-cement ratio was analysed by incorporating a greater proportion of supplementary cementitious materials into the cement.

2.2.1. *Description of the scenarios*

In this section, the description of the scenarios used in this research will be presented. Each scenario is subject to comprehensive clinker and cement production LCA. Table 1 offers a concise summary of the primary attributes of each scenario. The scenarios for 2030 and 2050 are set out below, aligning with the objectives outlined in the cement roadmap proposals for Spain and Europe (CEMBUREAU, 2020; Oficemen, 2020a).

Baseline scenario (2021). For the clinker LCA, the data on consumption of natural and alternative raw materials, fuels used in the kiln broken down into four types, and electricity are presented in Table 2 according to data from Oficemen (2022b). As seen in the inventory, all fuels and raw materials for preparing raw meal have been considered for the LCA, except those that are irrelevant because they are hardly used.

The thermal energy consumption is 3.6 GJ/t clinker. The thermal energy of fuels in the baseline scenario (Oficemen, 2022a) indicates than traditional fossil fuels account for 62.8 % of the annual fuel consumption, the vast majority being petcoke (58 %). Alternative fossil fuels (e.g., used mineral oil) account for 4.4 %. The rest of the fuels are divided up between biomass (10.9 %) and alternative fuels that are partially biomass (21.9 %), including Tyre-Derived Fuels (TDF) and Refused Derived-Fuel (RDF). In the case of RDF, their composition is not specified. For this reason, two alternative fuel models derived from waste were examined: RDF type A (RDF-A), which is made up of 60 % paper, 30 % plastics, and 10 % textiles, and RDF type B (RDF.B) which consists of 30 % paper, 60 % plastics, and 10 % textiles.

The inventory data used for the cement LCA are shown in Table 3, according to data from Oficemen (2022b). All cementitious raw materials are collected except those used residually.

Table 1
Summary of scenarios.

Scenarios	Clinker					Cement	
	Fuels (Thermal Energy %)				GJ/t clinker	Clinker ratio [%]	Gypsum & Cementitious material [%]
	Fossil Fuels %	Alternative Fossil Fuels %	Partially Biomass %	Biomass %			
Baseline 2021	62.8	4.4	21.9	10.9	3.6	82	18
2030	35.0	5.0	40.0	20.0	3.4	75	4.6 Gypsum & 20.4 Limestone
2050	5.0	5.0	50.0	40.0	3.3	65	4.6 Gypsum & 30.4 Limestone

Table 2
Inventory data referring to the LCA functional unit of clinker (1 t of clinker) in the baseline scenario (Oficemen, 2022b).

ELECTRIC ENERGY CONSUMPTION (MJ/t clinker)	328.39
CONSUMPTION OF RAW MATERIALS FOR THE PREPARATION OF RAW MEAL (kg/t clinker)	
NATURALS	
Clays	85.72
Sand	28.6
Sandstone	9.17
Limestone and other calcareous rocks	1117.40
Kaolin and kaolin clays	31.63
Calcareous Marl	268.79
Iron ores	5.15
Shales	19.55
Silica	5.42
ALTERNATIVES	
Iron waste	5.14
Raw black iron and steel slag	9.47
Other raw slags	6.21
Other raw alternative raw materials	5.65
Other recycled iron inputs	4.54
FUELS	
TRADITIONAL FOSSIL	
Imported petcoke	19.50
Domestic petcoke	43.96
Fuel oil furnaces	0.81
Fuel oil other facilities	0.03
Natural gas (m3/t clinker)	0.25
Gas oil other installations	0.02
Gas oil for furnaces	0.02
Imported coal	2.42
Domestic hard coal	2.59
Other traditional solid fuels	1.33
Domestic lignite	0.12
ALTERNATIVE FOSSIL	
Used mineral oil and emulsions	1.65
Solvents, varnish, paints and blends	1.88
Industrial sludges	0.02
Other non-biomass alternative liquids	1.12
Other non-biomass alternative solids	0.04
Plastics	0.08
Hydrocarbon liquid wastes	0.35
Wastes from end-of-life vehicles	2.04
Solid hydrocarbon wastes	0.18
ALTERNATIVE PARTIALLY BIOMASS	
Refused Derived-Fuel (RDF)	20.30
Tyre-Derived Fuels (TDF)	10.91
Impregnated sawdust or treated wood	1.83
ALTERNATIVE BIOMASS	
Vegetable biomass	8.54
Animal meal	5.70
Municipal sewage sludge	0.86
Wood waste	2.66
Other solid biomass alternative fuels	5.19

Table 3
Inventory data referring to the LCA functional unit of cement (1 t of cement) in the baseline scenario (Oficemen, 2022b).

ELECTRIC ENERGY CONSUMPTION (MJ/t cement)	159.91
CONSUMPTION OF RAW MATERIALS IN CEMENT MILLING (kg/t cement)	
NATURAL	
Limestone grinding cements	71.17
Gypsum ore and anhydrite	43.48
Other natural minorities cement	2.22
Pozzolans	19.76
ALTERNATIVE	
Recycled reducing agent	1.95
Cement grinding ashes	16.31
Cement grinding slag	11.46
Other cement alternative minorities	0.6
Artificial or recycled gypsum	2.84
Calcined shales	5.68

The clinker-to-cement ratio stands at 82 %. This ratio has been calculated based on the analysis of production data and the use of cementitious raw materials in 2021 (Oficemen, 2022b).

In future scenarios, according to the Spanish roadmap (Oficemen, 2020a), the use of biomass-derived fuels will increase, the clinker-to-cement ratio will be reduced, and thermal energy consumption will decrease through improved efficiency.

Scenario 2030: The fuel strategy includes utilizing 35 % of thermal energy from traditional fossil fuels, primarily petcoke, and 5 % from fossil-based alternative fuels. Additionally, 40 % of the fuel mix is comprised of partially biomass-derived alternatives, mainly including 27 % RDF, 12 % TDF, and 1 % sawdust. The strategy also incorporates 20 % biomass, which mainly consists of 13 % plant biomass, 3 % meal, and 1 % sludge. The thermal energy consumption in the kiln is estimated at 3.4 GJ/t clinker. Cement production uses a 75 % clinker-to-cement ratio, with the remaining 25 % made up of 4.6 % gypsum and 20.4 % limestone or pozzolan.

Scenario 2050: The proposed fuel strategy includes 5 % of thermal energy from traditional fossil fuels, primarily petcoke, alongside 5 % fossil-based alternative fuels. The mix also incorporates 50 % partially biomass-derived alternatives, detailed as 33 % RDF, 16 % TDF, and 1 % sawdust mainly. Additionally, 40 % of the fuel will come from biomass, comprising mainly 30 % plant biomass, 3 % meal, 4 % wood, and 1 % sludge. Regarding thermal energy consumption, a much more conservative scenario has been proposed compared to the one outlined in Spain's roadmap: 3.3 GJ/t clinker instead of 3.0 GJ/t clinker. Cement production uses a 65 % clinker-to-cement ratio, with the remaining 35 % made up of 4.6 % gypsum and 30.4 % limestone or pozzolan.

The availability of waste and biomass resources for use as alternative fuels has been assessed, and projections for 2050 estimate a demand of approximately 1 million tonnes of biomass, while agricultural residues in Spain already exceed 8 million tonnes, according to BIORAISE (2025). Additionally, waste resources such as RDF and TDF are sufficient to meet future needs, as Fundación CEMA & Institut Cerdà (2021) confirmed. These quantities are expected to grow further due to the enforcement of legislation restricting landfill disposal, which promotes waste recovery and its use as a sustainable resource.

It's notable that not all measures from the Spanish cement roadmap were applied in the LCAs due to challenges such as the uncertainty stemming from low commercial maturity of Carbon Capture Use (CCU) and Storage (CCS) technologies (European Commission, 2024). Current EU regulations prevent counting captured emissions for emitting industries under the EU Emission Trading Scheme if used for non-permanent purposes like recycled carbon fuels or RCFs (Directive (EU) 2023/959). Additionally, EU policies will ban non-biogenic or non-atmospheric carbon to produce RCFs by 2040 (Commission Delegated Regulation (EU) 2023/1185). These factors and the limited governmental support for CCS in Spain (Papeles de Energía, 2023) have excluded this technology from this study, along with a lack of conclusive data on its impact.

2.3. *Life cycle impact assessment (LCIA)*

The LCIA method chosen is the CML-IA baseline V3.08/developed by the Leiden Universiteit (PRé Sustainability, 2025). This method was favoured for its comprehensive scope, including all the most crucial impact categories, and its wealth of information. Moreover, it is based on a rigorous methodology and is continuously updated.

The impact categories in this LCIA method include: Abiotic Depletion Potential (ADP) in kg Sb eq, Abiotic Depletion Potential of Fossil Fuels (ADP-FF) in MJ, Global Warming Potential over 100 years (GWP100) in kg CO_2 eq, Ozone Depletion Potential (ODP) in kg CFC-11eq, Photochemical Oxidation Potential (POCP) in kg C_2H_4 eq, Acidification Potential (AP) in kg CO_2 eq, and Eutrophication Potential (EP) in kg PO_4^- eq. Additionally, the method evaluates four toxicity related categories: Human Toxicity Potential (HTP), Freshwater Aquatic Ecotoxicity

Potential (FAETP), Marine Aquatic Ecotoxicity Potential (MAETP), and Terrestrial Ecotoxicity Potential (TETP) all in kg 1.4-DCB eq.

3. Results and discussion

In this section, we discuss the results of the LCA conducted for clinker and cement in each of the evaluated scenarios. The findings from these studies offer a detailed insight into the environmental impact associated with each phase of the LCA of these materials, from the extraction of raw materials to manufacturing. This analysis helps identify opportunities for enhancing the sustainability of the products in each scenario studied.

3.1. Life cycle assessment of clinker production

Fig. 2 illustrates the percentage contribution of each stage in the clinker production process to the LCA results across various impact categories for the three scenarios analysed.

3.1.1. Baseline scenario 2021

This section presents the LCA results for clinker production in 2021 (baseline scenario). Two LCAs were conducted using biomass-derived fuels (RDF): type A (RDF-A) and type B (RDF-B). Since the results for both assessments were very similar, we will only present the findings derived from RDF-A. Fig. 2 illustrates the percentage contribution of six processing stages—raw materials, calcination, fuel usage (broken down by type) transportation, electricity, and infrastructure—to the impact categories, based on RDF-A data. In all categories, except for GWP100, fuel use represents the most significant contribution. Traditional fossil fuels, supplying 62.9 % of thermal energy, have the greatest impact on ADP-FF, HTP, MAETP, POCP, AP, and EP. In ADP, biomass-derived fuels dominate, while in ODP and FAETP, impacts are nearly equal between fossil and biomass-derived fuels. For TETP, the impact is split between

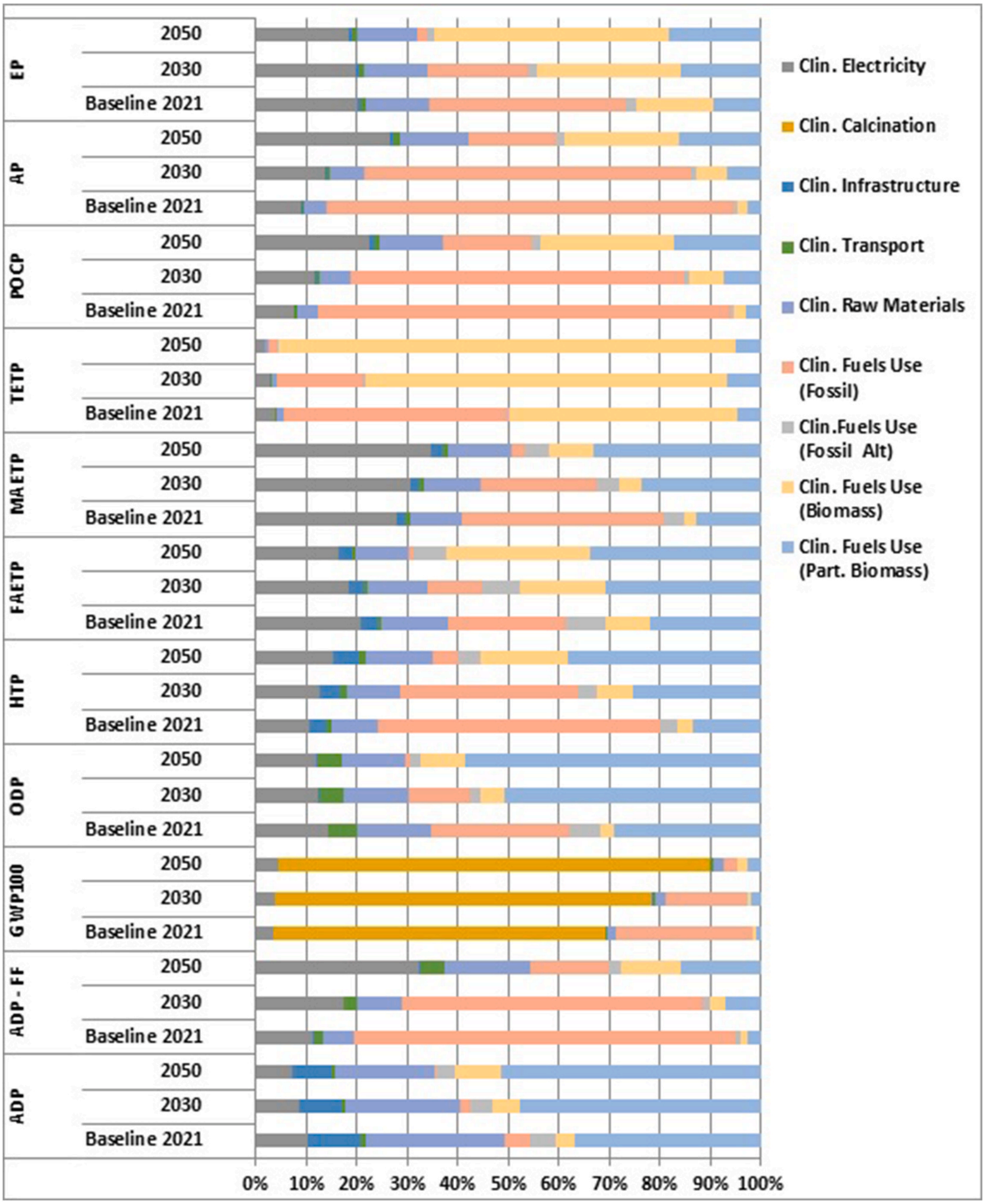

Fig. 2. Percentage contribution of each stage in the clinker production process to the LCA results across eleven impact categories for the three analysed scenarios.

fossil and biomass fuels. Electricity consumption accounts for more than 20 % of the impact on the FAETP, MAETP, and EP.

In the ADP category, fuels account for 50.7 % of the impact, with biomass-derived fuels (20 % of energy) contributing 36.9 %. Raw materials add 27.6 %, and electricity/infrastructure 20.9 %. For ADP-FF, fuel use dominates with 80.8 %, mainly from fossil fuels (75.8 %), followed by electricity (11.4 %) and raw materials (5.9 %).

As carbon dioxide costs rise in the cement industry, the GWP100 impact category becomes increasingly relevant. In 2021, the Spanish cement industry emitted 848 kg CO_2eq/t clinker produced. Approximately 65.9 % of these emissions resulted from the calcination of limestone (Cavalett et al., 2024; IEA, 2018; Pedraza et al., 2021). The second-largest contributor to emissions resulted from fuels (28.7 %), with fossil fuels making up 26.9 % of the total GWP100 impact. The contribution from electricity is relatively small, representing only 3.3 %. Additionally, the raw materials and their transportation from the quarry to the plant contribute a further 2 %.

In the ODP category, fuel use is the largest contributor at 65.2 %, mainly due to partially biomass-derived fuels (29.0 %) and fossil fuels (27.2 %), despite biomass fuels supplying only 20 % of the energy. This high impact is linked to emissions of chlorinated and brominated hydrocarbons during fuel production. Raw materials and electricity also contribute significantly, at 14.75 % and 14.2 %, respectively.

For the four ecotoxicity categories, fuel usage plays a significant role: contributing 94.5 % to TETP, 76.1 % to HTP, 62.1 % to FAETP, and 59.4 % to MAETP. Fossil fuels have the most significant impact in HTP, while fossil and partially biomass-based fuels influence FAETP, despite biomass contributing less energy. In the case of TETP, the fuels include both fossil and biomass sources. The impact is tied to the pollutants' persistence, toxicity, and exposure risk.

In the POCP category, fuel use contributes 87.8 % of the impact, with 81.6 % from mainly due to CO and NOx emissions. Electricity contributes 7.9 %, likely from fossil fuel sources. In the AP category, fuel make up 85.9 %, with 80.6 % from fossil fuels and 8.9 % from electricity. In the EP category, fuel use contributes 65.6 % of the total impact, with 38.9 % coming from fossil fuels and 24.7 % from all biomass fuels and electricity accounts for 20 %.

3.1.2. Scenario 2030

This section presents the analysis of the LCA results for the 2030 scenario (Table 1). Fig. 2 also highlights the percentage contribution of each stage of clinker production process across the 11 impact categories assessed. In the 2030 scenario, as in 2021, fuels use remains the main contributor to environmental impacts, except for GWP100. When comparing clinker production impacts between 2021 and 2030, six impacts categories decrease while five increase. The increase is linked to a higher share of thermal energy from biomass and partially biomass-derived fuels. Specifically, ADP, ODP, and FAETP are mainly affected by partially biomass fuels; TETP is associated with biomass fuels; and EP is influenced by both fuel types. Specifically, ADP, ODP, and FAETP are mainly affected by partially biomass fuels. TETP is associated with biomass fuel; EP is influenced by both fuel types of biomass. In the 2030 scenario, GWP100 emissions are 746.5 kg CO_2eq/t clinker, 12 % lower than in 2021, mainly due to reduced fossil fuel use.

3.1.3. Scenario 2050

The LCA results for the 2050 scenario (Table 1) are analysed below. Fig. 2 shows the impact values for producing one tonne of clinker in 2050 and the share of each stage in evaluated categories. Similar to the 2021 scenario, fuel use continues to generate the most significant impacts, except for GWP100. The 2050 scenario follows similar trends to 2030, with the same five impact categories increasing and six decreasing, though the changes are more pronounced in this scenario. For the five impacts that increase (ADP, ODP, FAETP, TETP, and EP), it's worth noting that the major contribution to the impact is not due to the use of fossil fuels but rather to alternative biomass fuels: ADP, ODP, and FAETP are mainly influenced by partially biomass fuels, whereas TETP and EP by biomass fuels.

In terms of GWP100, in the 2050 scenario, emissions are 652 kg CO_2eq/t clinker, representing a reduction of 23 % compared to the 2021 scenario. This reduction is primarily due to decreased use of traditional fossil fuels.

3.2. Life cycle assessment of cement production

Fig. 3 shows the percentage contribution of each stage in the cement production process to the LCA results, with the following sections analysing the impact categories for each scenario.

3.2.1. Baseline scenario 2021

Four additional stages of cement manufacturing (cement plant infrastructure, raw materials, electricity for grinding and transportation of cement raw materials) were considered alongside clinker production in the LCA of cement production. Fig. 3 shows the percentage contribution of the ten stages across environmental impact categories, with clinker production as the main contributor in most categories, except for ADP, where the additional stages for cement production account for 52.7 %. Clinker manufacturing is the main contributor to environmental impacts, accounting for 75–69 % in HTP, FAETP, and MAETP, and 83–97 % in the remaining categories. Fuel use is the key driver, contributing 75–90 % in TETP, POCP, AP, and ADP-FF; 50–60 % in ODP, HTP, and EP; under 50 % in FAETP and MAETP; and less than 24 % and 28 % in ADP and GWP, respectively.

A detailed GWP analysis reveals that cement production emits 718 kg CO_2 eq/t cement, with over 95 % of the emissions coming from the clinker stage mainly due to calcination (64.1 %) and fossil fuel use (26.25 %). Processes specific to cement production, contribute only 2.66 % to the total impact, highlighting that reducing the clinker content in cement is the most effective way to lower GWP.

In the ADP category, cement production phases contribute 52.7 % of the impact, mainly from plant infrastructure (47.3 %). Alternative fuel combustion, especially biomass, adds 17.4 %. For ADP-FF, fossil fuels are the main source (65.9 %), with electricity contributing 16.6 % due to higher use in cement production.

For ODP, fuel use accounts for 57.5 %, with 25.5 % coming from biomass-derived fuels. For ecotoxicity categories, while clinker production remains the most significant contributor, specific cement production stages also have a notable impact, except in the case of TETP.

3.2.2. Scenario 2030

In this scenario, cement is produced using 2030 clinker and a reduced clinker-to-cement ratio of 75 % (Table 1). The cementitious materials and gypsum make up the remaining 25 %, with limestone or pozzolan evaluated as options. Both alternatives yield similar results, though limestone shows slightly lower impacts. Moreover, Spain has widespread and abundant limestone reserves, supporting its use (Marchán and García Cortés, 2014).

Fig. 3 shows the impact of producing one tonne of cement across 11 categories using limestone as a supplementary cementitious material. When comparing the impacts of cement in 2030 with those of 2021, the same trend of increase or decrease is observed as in the case of clinker, mainly because the clinker production stage is the one that generates the greatest impact. The impact categories that show an increase are ADP, ODP, FAETP, and TETP and EP. The value for GWP100 is 585 kg CO_2eq/t cement, an 18 % reduction from 2021, due to lower clinker content and less reliance on fossil fuels.

3.2.3. Scenario 2050

As shown in Tables 1 and in addition to using clinker 2050, the clinker ratio is reduced to 65 %. The cementitious materials are increased up to 35 % along with gypsum. As cementitious materials, limestone or pozzolan are evaluated with similar results. A similar trend

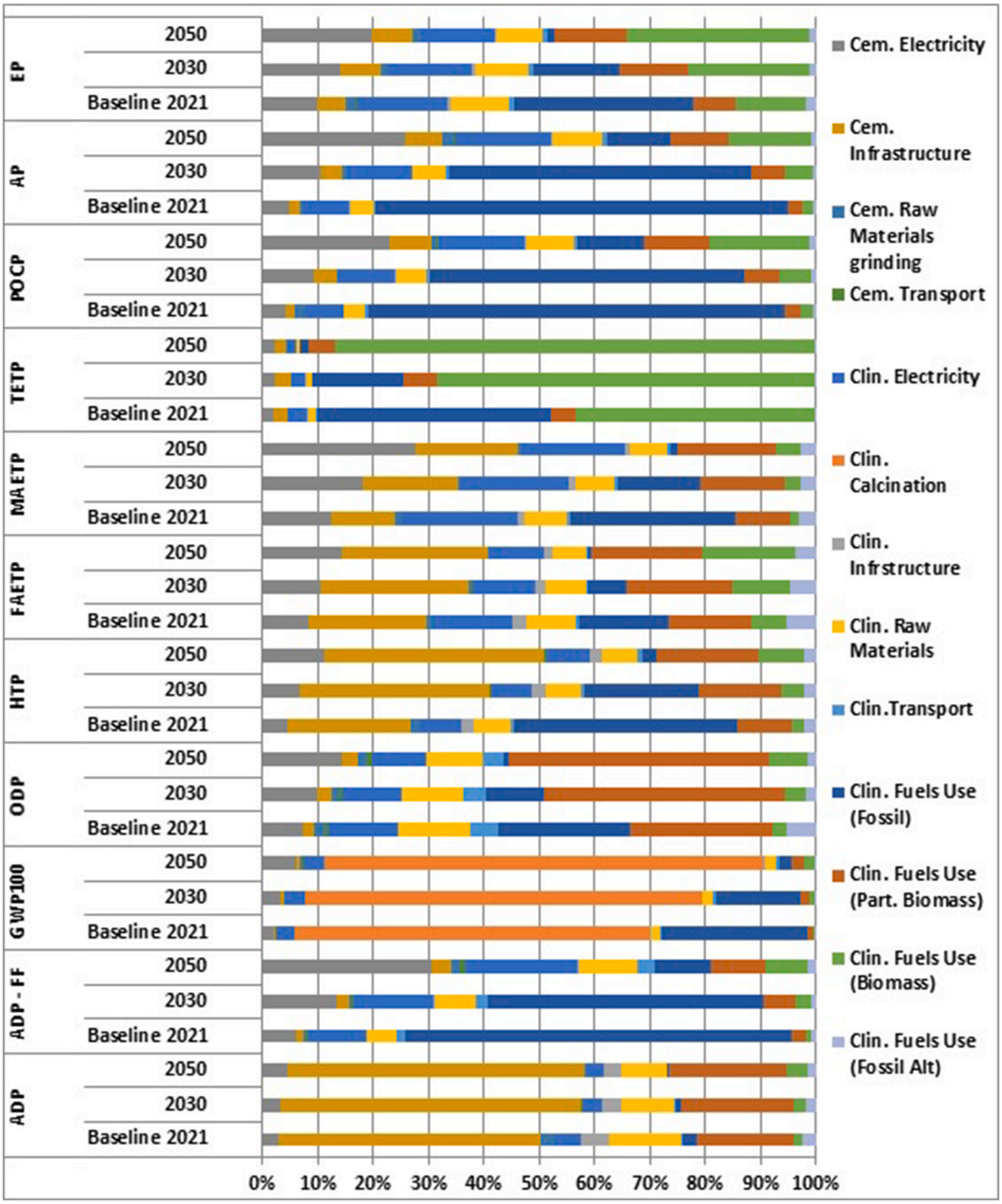

Fig. 3. Percentage contribution of each stage in the cement production process to the LCA results across eleven impact categories for the three analysed scenarios.

occurs to that in the 2030 scenario, but reductions and increases in impacts are more pronounced. The LCA results for this scenario are shown in Fig. 3, using limestone as a supplementary cementitious material. The GWP100 value is 457 kg CO_2eq/t cement, the lowest among those evaluated, as it contains less clinker and relies on a smaller proportion of fossil fuels, reduced by 36 %.

3.3. Comparison between scenarios

Figs. 4 and 5 illustrate the percentage changes in LCA results for clinker and cement production in the 2030 and 2050 scenarios compared to 2021, across the 11 evaluated impact categories. Additionally, Fig. 5 compares the effects of using limestone and pozzolan as supplementary cementitious materials. Both figures reveal a consistent trend: impacts increase in five categories and decrease in six, with the same categories affected in each instance. These changes are more pronounced in the 2050 scenario than in 2030. For clinker, reductions are observed in categories dominated by fossil fuel use, while increases are linked to a greater use of partially or fully biomass-based fuels. Cement exhibits a similar trend, as its environmental impacts are primarily determined by its clinker content. Furthermore, the findings indicate that employing either limestone or pozzolan as supplementary material results in virtually identical impacts. Notably, for both clinker and cement, the category with the most significant increase is TETP, which is closely linked to biomass fuel use.

The effects of the analysed decarbonisation measures are discussed below, focusing primarily on replacing fossil fuels with biomass-based alternatives and reducing the clinker-to-cement ratio in the evaluated scenarios for clinker and cement. The eleven impact categories are organized based on whether their values increase or decrease from 2021 to 2030 and 2050.

First, we will discuss the impact categories that experience an increase due to the applied decarbonisation measures: ADP, FAETP, ODP, TETP, and EP (Fig. 6). The increases in ADP and FAETP are primarily

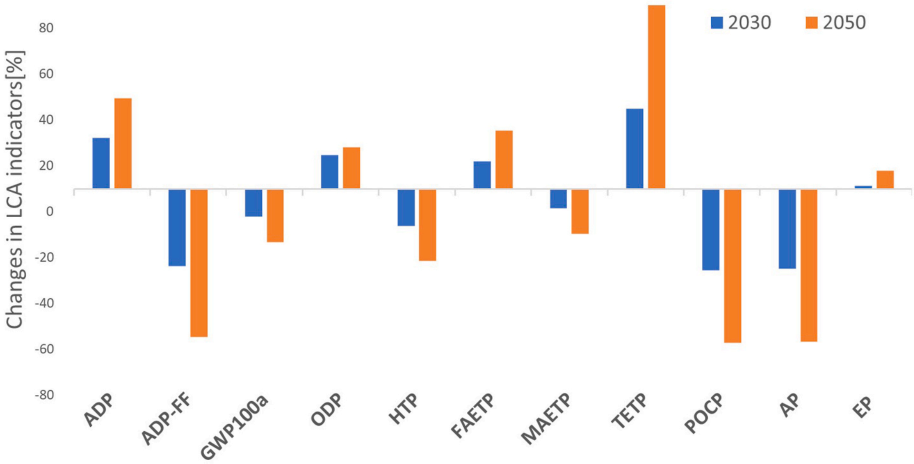

Fig. 4. Percentage changes in LCA results for clinker in the 2030 and 2050 scenarios compared to the 2021 baseline, across eleven evaluated impact categories.

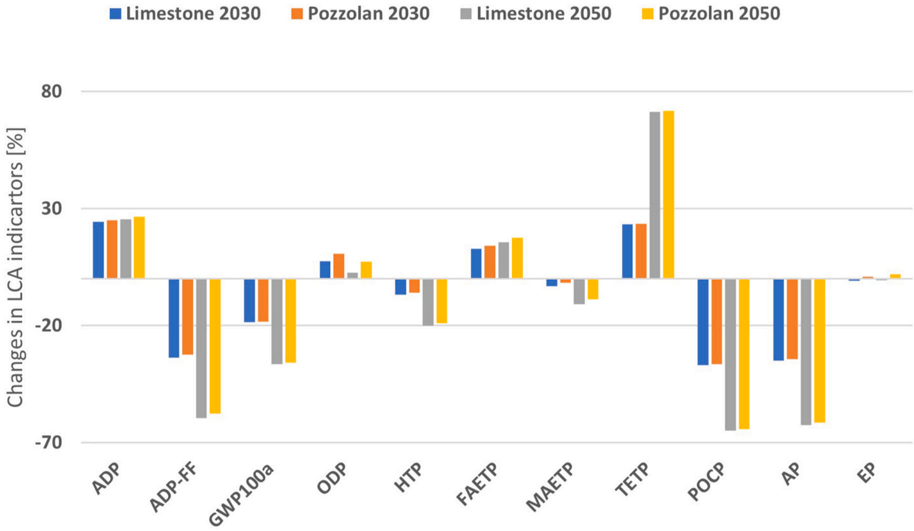

Fig. 5. Percentage changes in LCA results for cement containing limestone or pozzolan as supplementary materials in the 2030 and 2050 scenarios, compared to the 2021 baseline, across 11 impact categories.

attributed to the heightened use of biomass-derived fuels. In cement production, this impact is further magnified by additional processes, such as raw material extraction and elevated electricity consumption, all driven by the increased implementation of supplementary cementitious materials (SCMs). The rises observed in ODP and TETP are linked to the utilization of partially biomass-derived and fully biomass-based fuels, respectively. Regarding EP, the increase is a result of the combined use of fossil and biomass fuels. Although fossil fuel consumption is reduced, the concurrent rise in biomass use leads to relatively stable eutrophication values, with only minor variations across different scenarios. These categories are adversely affected by decarbonisation measures and should be considered critical when planning for the environmental performance of clinker and cement production.

A second group includes the impact categories that exhibit the opposite behaviour, showing a decrease as a result of the implementation of decarbonisation measures (Fig. 7). The reductions observed in ADP-FF, POCP, and AP are closely correlated with the diminished use of fossil fuels. As fossil fuel consumption declines, so too do the emissions produced during combustion, resulting in a significant improvement within these impact categories. Specifically, for GWP100, the reduction in impact during clinker production can be attributed primarily to the lower consumption of fossil fuels. This effect becomes even more pronounced in cement production, where a decreased clinker content significantly diminishes the emissions associated with the calcination process. Additionally, reductions in HTP and MAETP are noted, predominantly arising from the reduced use of fossil fuels. However, these improvements are less substantial, as fossil fuels play a smaller role in these particular impact categories. In summary, for these areas, the dual strategies of substituting fossil fuels with biomass-derived alternatives and reducing the clinker-to-cement ratio are beneficial for the future production of clinker and cement, as they contribute to lowering their associated impacts.

3.4. *Comparison with other studies*

This section offers a comparison between the findings of this study and those documented in existing literature. It is important to note that most LCA studies regarding to clinker and cement production predominantly focus on assessing the GWP of the process and exploring strategies for its reduction. Furthermore, these studies often differ in their scope, methodology, and the geographical or temporal contexts considered, which should be acknowledged when making comparisons.

In our study, we found that the GWP for clinker production was calculated to be 848 kg CO_2eq/t clinker in the 2021 baseline scenario.

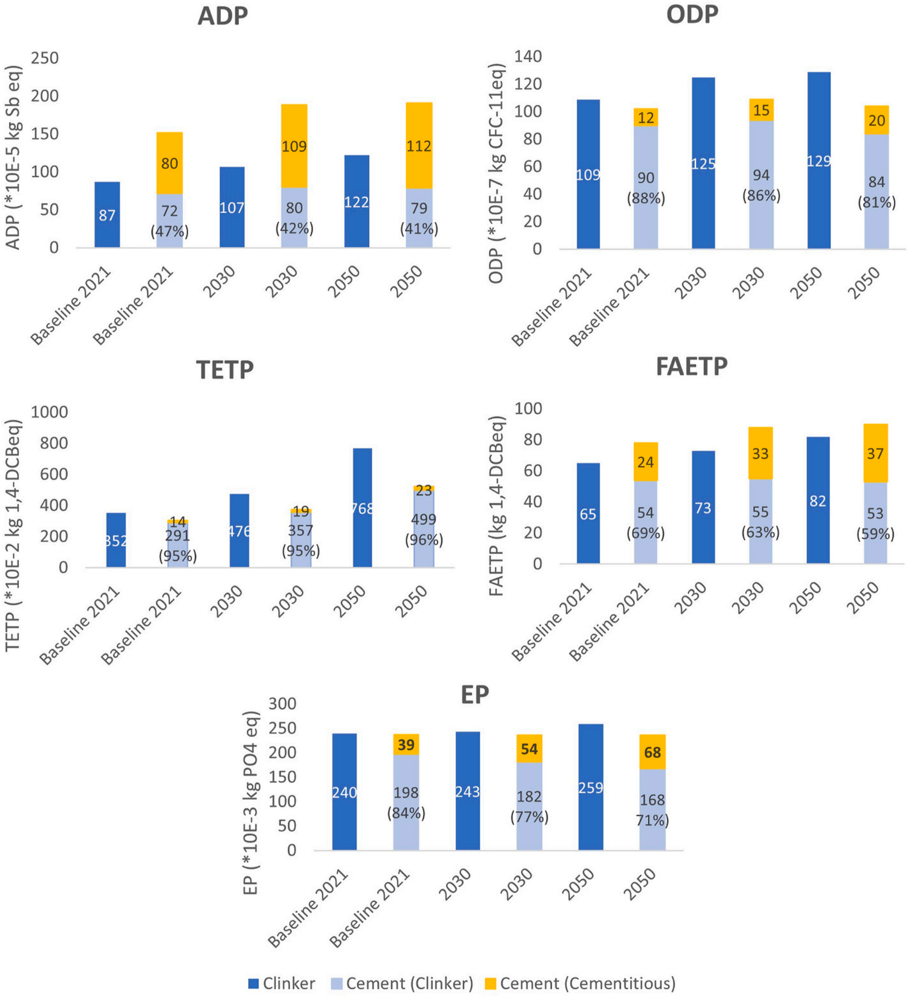

Fig. 6. LCA results for one tonne of clinker and cement in the three analysed scenarios, for the impact categories: ADP, ODP, TETP, FAETP, and EP.

This figure closely aligns with the results of Cavalett et al. (2024), who reported a weighted average of 926 kg CO_2eq/t clinker for European production. Their research underscores significant variations at the country level, with emissions ranging from 832 kg CO_2eq in Norway to 1,075 kg CO_2eq in Estonia. Similarly, Durastanti & Moretti (2024) analysed 41 clinker production formulations across Europe (2015–2023), reporting an average emission of 953 kg CO_2eq/t clinker, with values ranging from 849 to 1,042 kg CO_2eq/t, influenced by factors such as country, year, and methodology. Our result falls near the lower end of this range.

In our baseline scenario, we determined that the average global warming potential (GWP) for cement is approximately 718 kg CO_2eq/t. This aligns with Cherni et al. (2024), which reports a range of 732–831 kg CO_2eq/t based on cement type. Moretti and Caro (2017) also support these results, noting that variations in clinker content and supplementary cementitious materials significantly affect cement's environmental impact.

To achieve a more accurate comparison, the analysis will now focus specifically on clinker. This approach helps minimize variability that may arise from the differing compositions of cement. While GWP is the most commonly reported environmental impact, few studies expand their analysis to include other environmental categories. Furthermore, those that do often employ different LCA methodologies, which complicates comparisons between studies. To ensure consistency, our analysis emphasizes literature that uses the CML methodology in its various forms, thereby facilitating more reliable comparisons across multiple impact categories beyond GWP. Even with a unified methodology, there is still considerable variability due to the previously mentioned factors. In cement, this variability is increased by the various product formulations.

The values shown in Fig. 8 represent the base 10 logarithm of the ratio between the literature data, primarily based on the CML methodology, and this work's 2021 baseline clinker scenario (literature/this work). It is important to note that most of the referenced studies evaluate only a subset of the 11 impact categories included in our analysis. Significant differences exist not only between this work's baseline results and literature data but also among the references in the literature. These discrepancies can be primarily attributed to variations in methodology and differing study conditions, such as the year of study, geographic location, fuel type, and technologies used. Nonetheless, the results generally remain within the same order of magnitude.

An exception to this is the GWP category, where a high degree of consistency across various studies is observed. For other categories, such as POCP, AP, EP, and HTP, the results of this work fall within the reported ranges and demonstrate greater alignment with the existing literature. In contrast, the assessment of ADP-FF in this work is lower due to the fact that, in the baseline scenario, only 62.9 % of the energy input is derived from fossil fuels. Conversely, the relatively higher values we observed for ADP, FAETP, MAETP, and TETP are likely linked to the increased use of biomass-derived waste fuels in the analysis carried out in this study. The combustion of these residues typically results in elevated emissions of certain compounds, thereby increasing the impacts in those categories. Enhancing clarity and consistency in LCA methodologies could improve the reliability of environmental

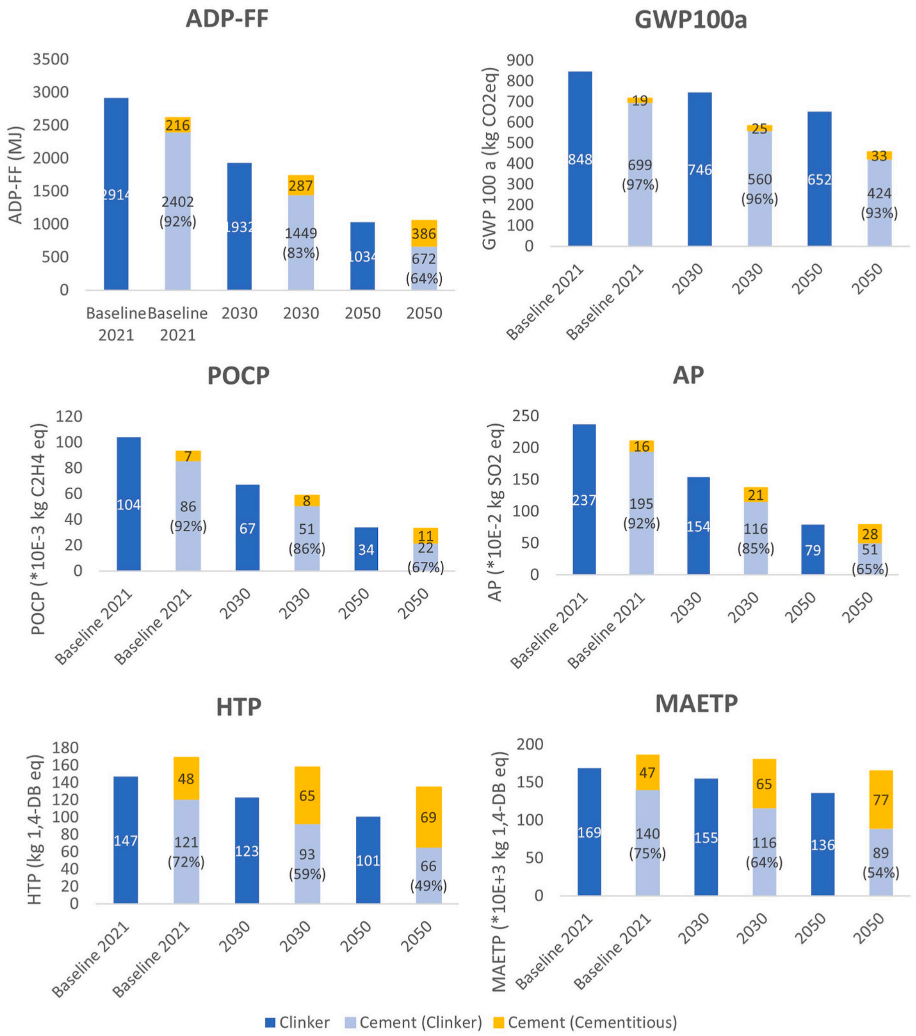

Fig. 7. LCA results for one tonne of clinker and cement in the three analysed scenarios, for the impact categories: for ADP-FF, GWP100, POCP, AP, HTP, and MAETP.

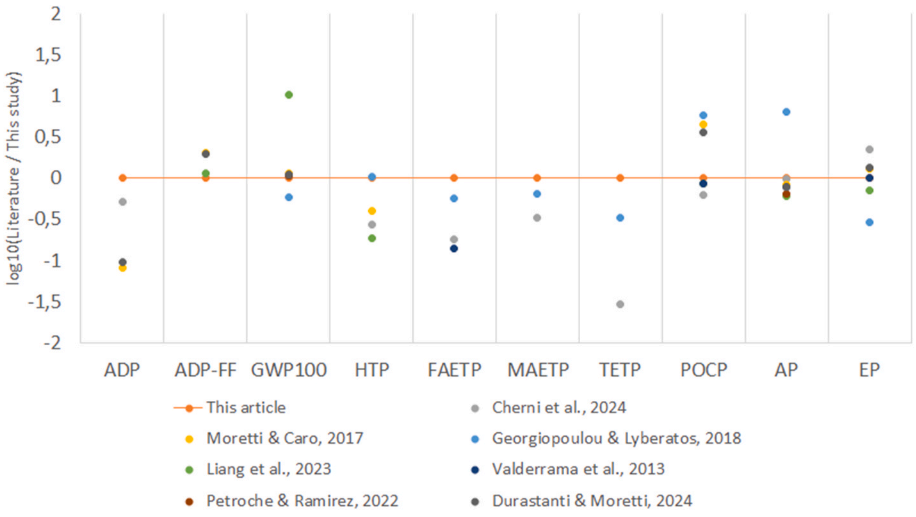

Fig. 8. Relationship between literature values and those from this study for clinker production in the evaluated impact categories, on a logarithmic scale.

assessments in the clinker and cement sector.

In addition, results have been compared across GWP scenarios, which serve as a key indicator to assess the impact of the decarbonisation measures proposed in the roadmap for the Spanish cement sector Oficemen (2020a). The strategies assessed include the substitution of fossil fuels with alternative fuels derived from waste, improvements in energy efficiency, and a reduction in the clinker-to-cement ratio. Implementing these measures led to a reduction in CO_2eq emissions of

12 % and 23 % per tonne of clinker, and 18 % and 36 % per tonne of cement, for the 2030 and 2050 scenarios, respectively in this study. These LCA results highlight the strong potential of the strategies to reduce CO_2 emissions and support national decarbonisation goals, though the reported reduction rates are not directly comparable to the official roadmap, which includes a wider range of mitigation actions and focuses mainly on direct CO_2 emissions. Other studies that corroborate the effectiveness of these measures in reducing CO_2 emissions include Çankaya and Pekey (2019), Mathioudakis et al. (2021), Kajaste and Hurme (2016)and Georgiades et al. (2023).

Recent studies, such as those by Müller et al. (2024) and Terán-Cuadrado et al. (2024), indicate that while decarbonisation strategies effectively reduce CO_2 emissions, they may shift environmental burdens to other impact categories. This observation, also noted in the present study, underscores the importance of conducting comprehensive environmental assessments considering multiple impact categories.

4. Conclusions

This study conducts cradle-to-gate LCAs for clinker and average cement production in Spain, comparing a 2021 baseline with future scenarios for 2030 and 2050. These future scenarios incorporate decarbonisation measures, including fuel substitution, improved thermal efficiency, and reduced clinker content.

The analysis indicates a clear trend: impact categories related to fossil fuel use, such as ADP-FF, GWP, HTP, MAETP, POCP, and AP, decrease as fossil fuel consumption declines. Conversely, categories affected by biomass-based fuel use, including ADP, ODP, FAETP, TETP, and EP, increase due to their higher usage. This pattern is observable in both clinker and cement production.

An important finding of this study is that the GWP results for clinker and cement production in the baseline scenario are consistent with scientific literature. However, expanding the LCA to include more environmental impact categories reveals methodological differences. While the results remain similar in magnitude, significant discrepancies arise between our findings and existing studies, as well as among those studies themselves. These variations suggest the importance of improving methodological harmonization in LCA to achieve more consistent and reliable environmental assessments in the clinker and cement sector.

The analysis of GWP scenarios demonstrates that the decarbonisation strategies evaluated in this study can lead to significant reductions in CO_2eq emissions within the cement sector. While the measures assessed have proven effective, this study does not consider other important actions outlined in the official roadmap, such as the use of decarbonized raw materials and the implementation of carbon capture, utilization, and storage (CCUS), which are identified as priorities for future research.

The implementation of decarbonisation strategies has transferred environmental burdens to other impact categories, resulting in increased specific values. This emphasizes the importance of considering potential trade-offs across different categories when designing and assessing mitigation measures. The alignment of these results with national decarbonisation goals underscores their significance for reducing CO_2 emissions in the cement industry.

CRediT authorship contribution statement

Ana María Santos-Montes: Writing – original draft, Supervision, Methodology, Data curation, Conceptualization. **Yolanda González-Arechavala:** Writing – original draft, Supervision, Methodology, Data curation, Conceptualization. **Carlos Martin-Sastre:** Writing – review & editing, Methodology, Conceptualization. **Léonard Lefranc:** Writing – review & editing, Supervision. **José Ignacio Linares:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

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

During the preparation of this work, the authors used ChatGPT to help with the writing process. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the published article.

Declaration of competing interest

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

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Appendix A. Map of the manufacturing of clinker and cement in Spain

Fig. 1 (Appendix A) shows 2021 clinker and cement production in Spanish plants, indicating production in tonnes per plant. Ten industrial groups operated 37 factories: 2 produce only grey clinker, 25 produce grey clinker and cement, 5 produce grey cement, 2 produce both grey and white clinker and cement, and 3 produce only white clinker (Oficemen, 2022b, 2023).

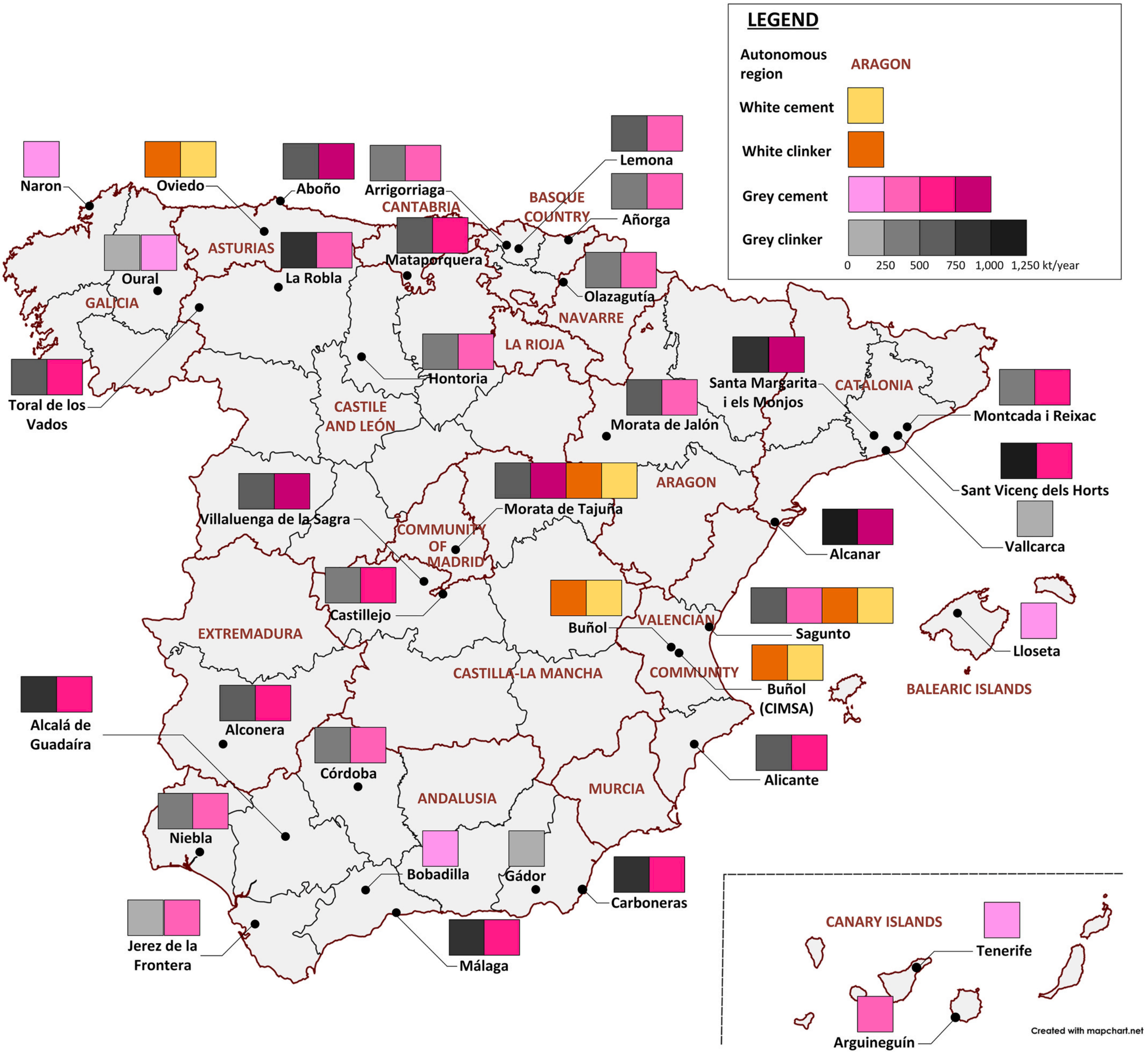

Fig. 1. Clinker and Cement Factories in Spain and their production in 2021.

In 2021, 16,800,011 tonnes of clinker were produced: 95.7 % grey (16,079,031 tonnes) and 4.3 % white (720,980 tonnes) (Oficemen, 2022b). Cement production followed a similar pattern, with 94.8 % grey (15,335,766 tonnes) and 5.2 % white (832,884 tonnes). A portion of the clinker was exported, leaving 12.7 million tonnes for producing 16.2 million tonnes of cement (Oficemen, 2022b).

Focusing on grey clinker production, the average production of the 29 Spanish factories in 2021 was 554,449 tonnes (Oficemen, 2022b). Excluding the two factories producing less than 3,550 tonnes, the average amounts to 595,390 tonnes, meaning an average factory produced approximately 600,000 tonnes in 2021. Regarding grey cement production, among the 32 factories considered, the average production was 479,243 tonnes, which became 510,933 tonnes, excluding the two factories with the lowest production.

White clinker and cement are only produced in five plants in Spain (Oficemen, 2022b, 2023). The three in the Valencia region contribute to approximately 70 % of the total white clinker and cement production.

The reduction in Spain's CO_2 emissions aligns with global trends, linked to post-2008 production declines and less CO_2-intensive clinker production, partly due to increased biomass use as fuel (Oficemen, 2020b, 2022b). The cement industry has reduced non-renewable energy use by co-processing waste as alternative fuels to align with circular economy principles. Kiln fuels are classified into traditional fossil fuels (mainly petcoke) and alternative fuels, which can be fossil-based, partially biomass-derived, or fully biomass-derived. From 2012 to 2021, alternative fuel use increased from 25.6 % to 37.1 % of total thermal energy, which is expected to continue (Institut Cerdà, 2023).

In 2021, fuel use varied across Spain's autonomous regions due to differing regulations on alternative fuels (Oficemen, 2022b). Some regions used over 90 % fossil fuels, while others, like Castilla-La Mancha (44.7 %) and Catalonia, the region with the highest production (46.3 %), were below 50 %. Notably, the San Vicent del Horts factory, Spain's largest producer, used only 38.1 % fossil fuels.

Using natural and alternative raw materials to manufacture raw meal for clinker production is important. The share of alternative materials in raw meal increased from 1.9 % in 2012 to 2.9 % in 2021 (Institut Cerdà, 2023). In 2021, 97.1 % of raw materials in Spain were natural, mostly limestone and marl (85.5 %), while 2.9 % came from industrial waste, with black steel slag being the most common (0.58 %) (Oficemen, 2022b).

Glossary

ADP	Abiotic Depletion Potential
ADP-FF	Abiotic Depletion Potential of Fossil Resources
AP	Acidification Potential
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
EP	Eutrophication Potential
FAETP	Freshwater Aquatic Ecotoxicity Potential
GWP 100	Global Warming Potential over 100 years
HTP	Human Toxicity Potential
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle inventory assessment
MAETP	Marine Aquatic Ecotoxicity Potential
ODP	Ozone Depletion Potential
POCP	Photochemical Oxidation Potenctial
RDF	Refuse-Derived Fuels
RDF-A	Refuse-Derived Fuel Type A
RDF-B	Refuse-Derived Fuel Type B
SCMs	Supplementary cementitious materials
TETP	Terrestrial Ecotoxicity Potential
TDF	Tyre-Derived Fuels

Data availability

Data will be made available on request.

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