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Process-Level Life-Cycle Assessment of Representative CEM II/A-L 42.5 R Cement: Environmental Hotspots and Decarbonisation Priorities

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Abstract

Cement manufacturing has a substantial environmental footprint driven by clinker production, calcination and thermal energy demand, yet many life-cycle assessment (LCA) studies report only aggregated results that offer limited guidance for process improvement. This study presents a cradle-to-gate, process-level LCA of CEM II/A-L 42.5 R cement, based on a cement composition representative of regional production practices and process data reflecting industrial manufacturing conditions. The production system was disaggregated into ten foreground processes, and impacts per tonne of cement were quantified with ReCiPe Midpoint (H) v1.11 in SimaPro. Inventory data were tiered by quality and reconciled against total results. Climate change was 772.2 kg CO_2-eq per tonne of cement, to which the rotary kiln contributed 67.7%, preheating and partial calcination 15.5%, and cement grinding 8.6%, together about 92%. Hotspots differed among the 17 interpreted midpoint categories (water depletion was excluded as a background-data artefact): the kiln led in eight, fuel preparation in five and cement grinding in four, including 97.8% of metal depletion, a result attributed to background datasets that requires verification. The climate change result had an estimated uncertainty of about ±11% (one standard deviation), reflecting the assigned data quality uncertainty and representing a lower bound on total uncertainty. The contribution-based ±30% sensitivity analysis showed that the total result was most responsive to changes in the kiln's assigned contribution, but did not independently test the underlying inventory assumptions. Kiln thermal optimisation, alternative fuels, clinker-ratio reduction and grinding electricity emerged as potential improvement priorities, while single-indicator assessment risks overlooking category-specific hotspots.

Keywords: clinker production; decarbonisation; process-level analysis; environmental hotspots; ReCiPe; uncertainty analysis; sensitivity analysis

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1. Introduction

Cement is among the world's most widely used building materials, and its production carries a heavy environmental burden. Most of it stems from clinker manufacturing, which requires high-temperature processing and releases greenhouse gases through both limestone calcination and fuel combustion, while raw material extraction, electricity and fuel use,

clinker cooling, and grinding add further impacts [1,2]. Reducing this burden requires attention to both cement composition and manufacturing efficiency.

Clinker content is one of the principal factors governing the environmental performance of cement. Replacing part of the clinker with mineral additions or alternative raw materials lowers the clinker-to-cement ratio and, with it, the associated environmental burden [1,3]. Recent studies confirm that supplementary cementitious materials, such as fly ash, ground granulated blast-furnace slag, metakaolin, calcined clays, and limestone, can reduce the global warming potential of cement, although the magnitude depends on the substitution rate, processing requirements, transport distances, allocation procedures, and the surrounding production system [4–7]. A cradle-to-gate inventory of a CEM II/A-L 42.5 R cement illustrates this mechanism, reporting approximately 0.63 kg CO_2-eq per kilogram of cement, underscoring the dominant role of clinker even in a limestone-blended cement [8]. Comparative life-cycle assessment (LCA) studies of CEM II/B-L and CEM II/B-V cements similarly show that higher clinker substitution reduces several midpoint impacts, with the extent varying by impact category and production context [9]. An assessment of CEM II/A-S and CEM II/B-V cements for heavy precast concrete showed that lower clinker content does not necessarily compromise mechanical performance, so environmental and technical trade-offs should be evaluated jointly [10]. Strength grade also shapes the environmental and economic profile of cement manufacturing, meaning that clinker substitution cannot be considered independently of strength-class requirements [11]. Replacing coal or petroleum coke in the kiln with refuse-derived fuel, biomass, sewage sludge, and other waste-derived fuels has been reported to reduce climate change impacts, depending on substitution rate and fuel type, while also diverting waste [12–14]. Prospective LCA studies indicate that clinker substitution, alternative fuels, improved kiln efficiency, and cleaner electricity supply act as complementary decarbonisation measures, with realised benefits depending on the surrounding production system [2,15,16].

LCA provides a systematic framework for quantifying environmental burdens across multiple impact categories, following ISO 14040 and ISO 14044 [17,18]. A cradle-to-gate boundary captures the burdens of raw material preparation, clinker production, and cement manufacture, but the full life-cycle performance of cement-based products also depends on later stages. Carbonation during service life and end-of-life can absorb CO_2 and alter the net climate change impact [19]. Environmental product declarations (EPDs) provide standardised, product-level environmental information under the core product-category rules for construction products [20] and their Serbian adoption [21], making them useful for benchmarking and communication. Recent reviews of cement LCA and EPD data show considerable variation in reported performance, even among comparable cements, owing to differences in clinker content, energy demand, system boundaries, background datasets, and production conditions [2,15]. A single aggregated value per tonne of cement reveals little about how the burden is distributed among production stages, such as raw material preparation, fuel use, calcination, clinker burning, and grinding.

A process-level LCA addresses this limitation by disaggregating the manufacturing system into individual operations and quantifying their contributions to the overall profile. Detailed process-level analyses have separated the contributions of raw material preparation, clinker burning, and grinding, and used this to evaluate variability between cement plants [22]. A stage-disaggregated assessment of a typical production chain identified calcination and grinding as the largest emitters and compared best-available technologies [23]. A cradle-to-gate assessment of limestone- and waste-containing cements showed that lower clinker content and alternative mineral constituents can reduce impacts, although additional processing may offset part of the benefit [7,24]. The CEM II/A-L 42.5 R inventory illustrates the weight of clinker production in the footprint of a limestone-blended cement [8]. Disag-

gregation is particularly valuable for cement because impact mechanisms differ: thermal clinker processes dominate greenhouse gas emissions, whereas electricity use and upstream supply chains may matter more for other categories [1,2,15]. However, studies vary in stage-specific reporting, impact categories considered, and treatment of data quality and uncertainty. The present study builds on this approach through a multi-category assessment that examines how data quality and modelling assumptions affect the interpretation of hotspots.

Recent investigations have highlighted substantial differences among cement LCA studies in system boundaries, functional units, allocation procedures, treatment of grinding energy, and clinker-to-cement ratios. These differences limit comparability and make it difficult to tell, from an aggregated indicator alone, how burdens are distributed within manufacturing [2,7,15,25]. The stage dominating climate change impact does not necessarily dominate other categories, so a climate-only assessment can miss hotspots linked to electricity, fuel supply, or upstream raw material processes [1,2,6,15]. The performance of blended cements therefore cannot be judged reliably from clinker content or global warming potential alone, as reductions in one category may come with changes in others [6,7].

The reliability of a process-level LCA also depends strongly on the quality and resolution of the life-cycle inventory. Industrial assessments typically combine primary measurements, calculated process flows, plant-level energy allocations, and background data from existing databases [26]. Treating all inputs as equally certain can mask key sources of uncertainty and obscure how strongly individual stages contribute, especially when a representative rather than plant-specific inventory is used [15,17,18]. Classifying inventory data by origin and reliability, consistent with the data quality requirements of ISO 14044 [18], therefore helps evaluate the robustness of the resulting profile. Reconciling stage-level contributions with the total LCA result also provides an internal consistency check on process scaling and functional-unit normalisation. Here, this check supports the transparency and consistency of the calculations [2,15,25].

Despite extensive application of LCA to cement production, the transparency and comparability of process-level assessments still need improvement. Existing studies, including a recent review of the effectiveness of LCA for gauging cement industry impacts [25], provide valuable performance estimates. However, differences in system boundaries, functional units, allocation procedures, inventory quality, and production assumptions complicate comparison and the interpretation of stage-level contributions [2,7,25]. Consistency between normalised process-level contributions and independently calculated total life-cycle impact assessment (LCIA) results is not always demonstrated, and the effect of data quality and uncertainty on stage-level conclusions is often insufficiently distinguished [27]. Reviews and studies have therefore called for greater methodological consistency and transparency, particularly regarding system boundaries, functional units, allocation, uncertainty analysis, and decarbonisation strategies [2,7,15,16].

The present study addresses this gap through a cradle-to-gate, process-level LCA of a representative CEM II/A-L 42.5 R cement on the Serbian market. Its novelty lies not in a new method but in combining ten-stage process-level disaggregation with explicit classification of inventory data by origin and reliability and an internal reconciliation check. This allows hotspot conclusions to be read in light of data quality. The study identifies stage-specific hotspots across multiple ReCiPe midpoint categories and assesses how data quality limitations and modelling assumptions affect the results. Reconciling stage-level contributions with the total results calculated in SimaPro serves as an internal consistency check on process scaling and functional-unit normalisation. These elements provide a detailed environmental profile of the production system and help identify process-level priorities for improvement. The system is divided into ten linked foreground processes:

raw material extraction and preparation, crushing and storage, raw material grinding, fuel preparation, preheating and partial calcination, rotary-kiln clinker production, clinker cooling, cement grinding, cement storage, and packing and plant-gate dispatch. This structure allows the contribution of each stage to be quantified and compared per functional unit of 1 tonne of cement, using the ReCiPe Midpoint (H) V1.11 framework [28].

The overall objective of this study is to conduct a transparent, process-level, cradle-to-gate LCA of a representative CEM II/A-L 42.5 R cement, linking its environmental profile to the contributing production stages and examining how inventory-data quality and modelling assumptions affect the interpretation of hotspots. The specific objectives are to (1) establish a transparent cradle-to-gate life-cycle inventory for the cement system, with data classified by origin and reliability; (2) quantify the impacts of 1 tonne of cement using the ReCiPe Midpoint (H) V1.11 framework; (3) quantify the contribution of individual production stages to climate change and other midpoint categories, and reconcile them with the total impact results; (4) identify the principal environmental hotspots; (5) evaluate the influence of data quality and modelling assumptions on the results; (6) assess the sensitivity of the climate change result to the most influential parameters or stages; and (7) identify process-level priorities for reducing environmental burden.

2. Materials and Methods

2.1. Cement

The cement considered in this study is a representative, CEM II/A-L 42.5 R cement intended to reflect commercially available cement products on the Serbian market. According to SRPS EN 197-1 [29], CEM II/A-L is a Portland-limestone cement in which Portland clinker is the principal constituent and limestone is the main additional constituent. The designation "A" denotes a clinker content of 80–94% by mass, "L" indicates limestone as the main additional constituent (6–20% by mass), "42.5" denotes the standard strength class, and the suffix "R" indicates high early-strength development. The representative cement characteristics used in this study were established from data obtained for three CEM II/A-L 42.5 R cements available on the Serbian market. To avoid dependence on the characteristics of an individual manufacturer or production facility, the reported values represent averages across these three products rather than the specification of a single commercial brand. Because two of the three cements contained small amounts of granulated blast-furnace slag in addition to limestone, the representative composition was constructed to reflect the aggregate characteristics of this product group. In EN 197-1, the composition limits refer to the sum of the main and minor additional constituents, excluding calcium sulphate and additives. The representative composition (775 kg clinker, 134 kg limestone, 48 kg granulated blast-furnace slag, and 43 kg gypsum per tonne of cement) corresponds to approximately 81.0% clinker, 14.0% limestone, and 5.0% slag when expressed on the EN 197-1 basis, i.e., excluding calcium sulphate. This is within the 80–94% clinker range and the 6–20% limestone range specified for CEM II/A-L, with slag at 5.02%, marginally above the 5% limit for minor additional constituents. The limestone content was not verified by direct measurement of $CaCO_3$ (e.g., by TGA or CO_2 analysis), and limestone purity was not determined separately.

The chemical composition of the three commercial cements was determined by energy-dispersive X-ray fluorescence (ED-XRF) according to SRPS EN 196-2 [30], using a Spectro Xepos spectrometer (Spectro Analytical Instruments GmbH, Kleve, Germany) [31]. Loss on ignition (LOI) was determined by heating the samples at 1000 °C in a laboratory furnace. The physical and mechanical characteristics [29,32,33] presented in Table 1 were measured for the three commercial products and are reported as representative mean values.

Table 1. Chemical, physical, and mechanical properties of representative CEM II/A-L 42.5 R cement.

Cement CEM II/A-L 42.5 R Characteristics			
Chemical composition		Physical properties	
CaO (wt.%)	60.5		
SiO_2 (wt.%)	20.1	Particle density (g/cm^3)	3.05
Al_2O_3 (wt.%)	4.2	Bulk density (kg/m^3)	1230
Fe_2O_3 (wt.%)	3.1	Blaine specific surface (cm^2/g)	4350
MgO (wt.%)	2.18	Initial setting time (min)	175
SO_3 (wt.%)	3.0	Final setting time (min)	235
Na_2O (wt.%)	0.25	Soundness (Le Chatelier) (mm)	1.5
K_2O (wt.%)	0.70	Standard consistency (%)	30
TiO_2 (wt.%)	0.25	Mechanical properties	
P_2O_5 (wt.%)	0.14		
LOI (wt.%)	4.36	Compressive strength, 2 d (MPa)	31.5
Insoluble residue (wt.%)	1.2	Compressive strength, 7 d (MPa)	44.7
Chloride (Cl^-) (wt.%)	0.02	Compressive strength, 28 d (MPa)	53.4

The materials considered in the representative cement composition were sourced in Serbia; however, supplier identities and supplier-specific commercial information cannot be disclosed due to confidentiality restrictions.

2.2. Life-Cycle Assessment

The LCA was conducted using SimaPro software, version 8.0.4.7 (PRé Sustainability, The Netherlands), to quantify the environmental impacts associated with the production of the representative CEM II/A-L 42.5 R cement defined in Section 2.1. The assessment followed the principles and framework of ISO 14040 and ISO 14044 [17,18]. A cradle-to-gate system boundary was adopted, covering cement production from raw material extraction to the finished product at the plant gate, and the production chain was divided into ten stages (P1–P10; Table S1). The functional unit was 1000 kg of cement, with the composition taken from Section 2.1.

Foreground process data (fuel mix, electricity consumption and emissions) originate from a single plant and were normalised to the representative composition, which was established from laboratory analysis of cements from three plants. Each data point was assigned to one of four quality tiers (Table S1). Background data were taken from ecoinvent v3.1 (cut-off by classification), under which secondary fuels and slag carry no upstream burdens, and electricity was modelled with the "Market for electricity, medium voltage, RS (Serbia)" dataset. Impacts were calculated using the ReCiPe Midpoint (H) V1.11 method [28]. Climate change (Global warming potentials over a 100-year time horizon (GWP_{100}) were used to convert greenhouse gas emissions into CO_2-equivalents, based on the values reported by the IPCC (2007)) is the principal indicator, and other categories may differ under ReCiPe 2016 or EF 3.1, which were not applied. The 2014 background database is also older than the plant data. The cement production scenario and principal LCA parameters are given in Table 2.

Table 2. Cement production scenario and principal LCA parameters used in the assessment.

Parameter	Value
Goal and scope	
Cement type	CEM II/A-L 42.5 R
Functional unit	1000 kg of cement
Reference flow	1000 kg of cement at plant gate
System boundary	Cradle-to-gate
Geographical scope	Serbia; production scenario representative of Serbian market
Process stages modelled	10 (P1–P10)
Cement composition (per tonne)	
Clinker	775 kg (81.0% of main and minor constituents, EN 197-1 basis)
Non-clinker fraction	225 kg *
Raw material requirement for P1/P2	1025.3 kg/t cement
Raw-mix-to-clinker ratio	1.323 t/t clinker
LCA modelling	
Software	SimaPro 8.0.4.7 (PRé Sustainability, Netherlands)
Background database	ecoinvent v3.1, cut-off by classification
Electricity dataset	Market for electricity, medium voltage, RS (Serbia), ecoinvent v3.1, cut-off by classification
LCIA method	ReCiPe Midpoint (H) v1.11 [28]
Sensitivity and uncertainty analysis	
Process-stage sensitivity	Deterministic one-at-a-time ±30% perturbation of process-stage contributions
Overall climate change uncertainty	Estimated relative uncertainty of ±11% (one standard deviation), calculated by variance-weighted propagation of assigned process-level coefficients of variation (15–25%)
Selected results	
Climate change (GWP100)	772.2 kg CO_2-eq/t cement

* The 225 kg/t value is the balance between 1000 kg of cement and 775 kg of clinker. Its breakdown (134 kg limestone, 48 kg granulated blast-furnace slag and 43 kg gypsum) is given in Sections 2.1 and 2.2.2.

2.2.1. Goal and Scope Definition

The primary goal of the LCA was to quantify the environmental impacts associated with the production of CEM II/A-L 42.5 R cement and to identify the relative contribution of individual production stages to the overall environmental profile. The study was designed to establish a process-level environmental baseline and to identify the principal environmental hotspots within the production system. The baseline supports the identification of opportunities for improving environmental performance and the evaluation of potential decarbonisation measures. It also provides a reference for future comparison with alternative cement compositions and for assessing supplementary cementitious material substitution scenarios. The study is not intended for comparative assertions disclosed to the public. The intended audience comprises cement producers, environmental researchers, LCA practitioners, engineers, and researchers investigating lower-carbon cement production. The

investigated cement is the representative composition defined in Section 2.1, which reflects CEM II/A-L 42.5 R cements on the Serbian market rather than a specific commercial brand, whereas the process data originate from a single plant. The results therefore describe a market-representative recipe produced with single-plant process data and should not be read as a market-average environmental profile.

2.2.2. Functional Unit

The functional unit was defined as 1 tonne (1000 kg) of CEM II/A-L 42.5 R cement at the plant gate (Table 2). All material, energy, and emission flows included in the LCA were normalised to this functional unit. For the purposes of the process model, the investigated cement was represented by the composition defined in Section 2.1: 775 kg clinker, 134 kg limestone, 48 kg granulated blast-furnace slag, and 43 kg gypsum per tonne of cement. Expressed on the EN 197-1 basis (excluding calcium sulphate and corresponding to 957 kg of main and minor constituents per tonne), this corresponds to 81.0% clinker, 14.0% limestone and 5.0% slag (5.02%, marginally above the 5% limit for minor additional constituents; see Section 2.1).

These quantities were used as the basis for scaling the individual production stages within the LCA model. Stages P1–P2 were scaled by 1.025349 (1.323031 t raw mix per t clinker × 0.775 t clinker per t cement), stages P3–P7 to the clinker requirement of 0.775 t per t cement, and stages P8–P10 were modelled directly per tonne of cement (Table S2). The 775 kg clinker quantity represents the clinker requirement adopted in the investigated LCA scenario and should not be interpreted as the annual average clinker factor of a particular cement plant or as a generalised clinker content for all CEM II/A-L cements available on the Serbian market. As noted in Section 2.1, this figure reflects the aggregate composition of commercial cements that contain slag in addition to limestone and is therefore not a strict CEM II/A-L formulation with limestone as the only additional constituent.

2.2.3. System Boundary

A cradle-to-gate system boundary was adopted. The system begins with the extraction and preparation of the raw materials and ends with the production of finished cement at the plant gate. The modelled system comprises ten foreground stages (P1–P10; Table 3): quarry raw material extraction and preparation (P1); crushing, internal transport and raw material storage (P2); raw material grinding and homogenisation (P3); storage, grinding and dosing of fuels (P4); four-stage cyclone preheating and partial calcination (P5); rotary-kiln calcination, transition and sintering (P6); grate clinker cooling and transport to the silo (P7); cement production by grinding clinker with additions (P8); cement storage in silos (P9); and cement packing, palletising and plant-gate dispatch (P10). Upstream production of fuels, electricity, limestone, gypsum, sand and slag is included through the ecoinvent background datasets. Packaging materials and natural gas were not modelled (Table S1), so P10 comprises electricity use and dust emissions only.

The use phase, transport after the plant gate, application of cement in construction products, and end-of-life processes were outside the defined system boundary. This system boundary corresponds to a product-stage assessment (modules A1–A3 of EN 15804 [20,21]), in which the environmental burdens of cement production are considered up to the point at which the finished product leaves the manufacturing system.

Table 3. Definition of the foreground process stages included in the cement-production model.

Code	Production Stage	Main Operations Represented
P1	Quarry raw material extraction and preparation	Extraction of limestone and marl, initial preparation and handling
P2	Crushing, internal transport and raw material storage	Crushing, internal material transport and storage of prepared raw materials
P3	Raw material grinding and homogenisation	Grinding of raw materials and homogenisation of the raw meal
P4	Storage, grinding and dosing of fuels	Fuel storage, preparation/grinding and controlled fuel dosing
P5	Four-stage cyclone preheater and partial calcination	Preheating of raw meal and partial thermal decomposition/calcination
P6	Rotary kiln—calcination, transition and sintering	Final calcination, clinker mineral formation, transition and sintering
P7	Grate clinker cooler and transport to silo	Cooling of clinker and transport to clinker storage
P8	Cement production—clinker grinding with additions	Grinding of clinker with cement constituents/additions and production of cement
P9	Cement storage in silos	Storage of finished cement prior to dispatch
P10	Cement packing, palletising and plant-gate dispatch	Cement packing, palletising and dispatch to the plant gate

2.2.4. Process-Level Production Model

The cement-production system was represented by ten foreground processes (P1–P10), as summarised in Table 3.

The available plant information identifies a four-stage cyclone preheater, but the presence of a separate precalciner could not be confirmed from the inventory documentation. P5 is therefore defined in the LCA model as the preheating and partial calcination stage, not as a verified precalciner unit.

This process decomposition was used to determine the contribution of individual stages to the environmental impacts calculated for the functional unit. Stages P7 (clinker cooler) and P9 (cement storage) show zero impacts in all evaluated categories. This reflects data availability and model structure, not an absence of environmental burden. Their electricity use (cooler fans, hydraulics and conveying; silo aeration and transfer) was not sub-metered. Total plant electricity was allocated to other stages using plant-stated shares (P3, P6, P8 and P10; Table S1), so these consumptions are captured in the model, mainly within P6, but are not attributed to P7 and P9. The only quantified flows of P7 and P9 are the links to the preceding stage, whose impacts are already counted in P6 and P8, and, for P7, a total particulate emission from the cooler stack. The impacts of clinker cooling and cement storage are therefore embedded in other stages, a limitation noted in Section 4.9.

2.2.5. Life-Cycle Inventory

The life-cycle inventory (LCI) combines plant-specific process data, calculated quantities, modelling assumptions, and external technical or LCA database information. Each inventory item was assigned to one of four tiers according to its methodological basis: Tier 1, measured or plant-provided data; Tier 2, values calculated from such data through mass balances, scaling, normalisation to the functional unit or allocation; Tier 3, modelling assumptions and estimates introduced where process information was not directly available; and Tier 4, values from published literature, emission factors or LCA databases. This classification makes the origin and quality of the inventory data transparent.

Annual plant data (fuel consumption, emission rates and operating hours) were normalised to clinker production and converted to the functional unit using the clinker requirement of 0.775 t per t cement. Total electricity consumption (midpoint of 110.25 kWh/t cement within a supplied range of 107–113.5 kWh/t cement) was allocated to the process stages using plant-stated shares. Two CO_2 flows rest on assumptions and estimates rather than plant measurements. Calcination CO_2 was derived from a 515 kg/t clinker mass loss, based on an assumed raw-meal loss on ignition of 34% (BREF range 32–36%) and split 30/70 between preheater and kiln as a modelling assumption rather than a plant-measured distribution. Because this split could not be verified (Section 2.2.4), the individual P5 and P6 contributions should be interpreted as assumption-dependent model results. Fuel-combustion CO_2 was estimated from the documented fuel mix (petroleum coke, coal, solid recovered fuel and waste tyres) using fuel-specific net calorific values, IPCC default emission factors and fossil/biogenic fractions, giving 279.2 kg fossil and 61.91 kg biogenic CO_2 per tonne of clinker. Together, the calcination and fossil fuel-combustion CO_2 account for about 80% of the climate change result, so their influence is examined in the sensitivity analysis, and the resulting limitations are discussed in Section 4.9.

The combined contribution of P5 and P6 is approximately 83.2% of the calculated climate change impact under the adopted inventory assumptions. It is less sensitive to the allocation of calcination CO_2 between the two stages than their individual contributions, provided that total calcination emissions remain unchanged, but it depends on the estimate of total calcination CO_2, including the assumed raw-meal loss on ignition.

The complete life-cycle inventory for process stages P1–P10, including the main inputs and outputs, data tier, and source of each inventory item, is provided in Supplementary Table S1. Amounts are reported for the SimaPro reference output of each process stage and converted to the functional unit of 1000 kg of cement.

2.2.6. Mass Balance and Process Scaling

The individual production stages were normalised to the functional unit of 1000 kg of cement at the plant gate. The raw material requirement was determined from the mass balance per tonne of clinker. A raw meal of 1515 kg, derived from an assumed raw-meal loss on ignition of 34%, comprises 1323.031 kg of crushed raw mix (87.33%), 105.436 kg of corrective limestone, 55.854 kg of sand and 30.679 kg of metallurgical slag. Calcination causes a mass loss of 515 kg, treated as CO_2 (154 kg in the preheater and 361 kg in the kiln), leaving 1000 kg of clinker.

With 0.775 t of clinker per tonne of cement and 1.323031 t of crushed raw mix per tonne of clinker, a scaling factor of 1.025349 was applied to P1 and P2. A factor of 0.775 was applied to P3–P7, and P8–P10 were modelled directly on a basis of 1000 kg cement (factor 1.0). The SimaPro comparison amounts, required amounts and scaling factors are listed in Supplementary Table S2. This procedure allowed the impacts of all stages to be expressed consistently per 1000 kg of cement at the plant gate.

2.2.7. Life-Cycle Impact Assessment

The life-cycle impact assessment (LCIA) was performed in SimaPro using the ReCiPe Midpoint (H) V1.11 method [28], which applies the hierarchist perspective. The midpoint approach was selected to quantify the burdens of individual impact pathways and to identify the production stages contributing most to each category. Eighteen midpoint categories were calculated (climate change; ozone depletion; terrestrial acidification; freshwater eutrophication; marine eutrophication; human toxicity; photochemical oxidant formation; particulate matter formation; terrestrial ecotoxicity; freshwater ecotoxicity; marine ecotoxicity; ionising radiation; water depletion; metal depletion; fossil depletion; agricultural land occupation; urban land occupation; and natural land transformation); water depletion was excluded from the interpretation (Sections 2.2.9 and 3.1), so hotspots are reported for 17 categories. All results are expressed per functional unit of 1 tonne of cement at the plant gate.

2.2.8. Model Verification and Reconciliation

To verify the consistency of the process-level model, the contributions of stages P1–P10 were summed for each impact category for which a SimaPro total was available (15 of 18) after normalisation to 1000 kg of cement and compared with the total LCIA result for the complete SimaPro model. The sums agreed with the totals within numerical rounding tolerance for all 15 categories (maximum relative deviation: 4.31×10^{-7}%). For climate change, the sum was 772.215 kg CO_2-eq/t cement against a total of 772.215 kg CO_2-eq/t cement, a difference of approximately 8.4×10^{-8}%. Totals were not available in the exported SimaPro results for the three land-use categories (agricultural land occupation, urban land occupation and natural land transformation), so reconciliation could not be performed for them. This check confirmed that the scaling, allocation of impacts among stages P1–P10 and normalisation to the functional unit did not introduce a material discrepancy between the stage-level inventory and the complete model, but it verifies only arithmetic consistency and does not validate the underlying inventory data. Detailed reconciliation results are provided in Supplementary Table S3.

2.2.9. Treatment of Impact Contributions

The calculated impact results were retained in their original SimaPro form. The land-use-related categories (agricultural land occupation, urban land occupation and natural land transformation) were retained in the dataset but were not included in the graphical summary to improve readability. Water depletion was calculated but excluded from the interpretation because its net result (−1085.755 m^3 per tonne of cement) is not a physical water flow (Section 3.1). Small negative contributions to natural land transformation were retained as reported by SimaPro. The plotted shares therefore refer to the sum of absolute stage contributions and do not add up to the net result. This treatment was limited to the graphical presentation and did not modify the SimaPro results.

Stages P7 (clinker cooler) and P9 (cement storage) show zero impacts in all evaluated categories (Section 2.2.4), which is treated as a limitation of the process model (Section 4.9). The sensitivity and uncertainty analyses were applied to the climate change result. Sensitivity was assessed using a deterministic one-at-a-time ±30% perturbation of the contribution of each process stage, while all other contributions were held constant, and the resulting change in the total was expressed as a percentage of the baseline total. The estimated relative uncertainty of the climate change result, ±11% (one standard deviation; Table 2), was obtained by assigning a coefficient of variation of 15–25% to each process stage according to data quality and reliability, applying it to the corresponding climate change contribution, and propagating these uncertainties by variance-weighted summation, assuming inde-

pendent contributions. This estimate did not involve a probabilistic Monte Carlo analysis. Uncertainty associated with background data and the LCIA method was not independently quantified and is treated as a structural limitation of the assessment (Section 4.9).

3. Results

3.1. Overall Life-Cycle Impact Assessment Results

The life-cycle impact assessment results for the production of 1 t of representative CEM II/A-L 42.5 R cement are summarised in Table 4. Eighteen midpoint categories were calculated, of which 17 were interpreted (water depletion was excluded; Section 3.1). Evaluation was conducted using the ReCiPe Midpoint (H) V1.11 method [28,34]. The findings show that cement manufacture is not a single-issue environmental process. It contributes to toxicity-related, resource-depletion-related, and emission-related categories at the same time.

Table 4. Life-cycle impact assessment results for 1 t of CEM II/A-L 42.5 R cement at the plant gate.

Parameter	Unit	Value
Climate change	kg CO_2-eq	772.215
Ozone depletion	kg CFC-11 eq	9.575×10^{-6}
Terrestrial acidification	kg SO_2 eq	2.090
Freshwater eutrophication	kg P eq	3.305×10^{-2}
Marine eutrophication	kg N eq	5.223×10^{-2}
Human toxicity	kg 1,4-DB eq	8.464
Photochemical oxidant formation	kg NMVOC	1.327
Particulate matter formation	kg PM_{10} eq	0.815
Terrestrial ecotoxicity	kg 1,4-DB eq	8.685×10^{-3}
Freshwater ecotoxicity	kg 1,4-DB eq	7.734×10^{-2}
Marine ecotoxicity	kg 1,4-DB eq	9.714×10^{-2}
Ionising radiation	kBq U-235 eq	4.532
Agricultural land occupation	m^2·a	1.537
Urban land occupation	m^2·a	0.974
Natural land transformation	m^2	2.306×10^{-3}
Water depletion	m^3	excluded
Metal depletion	kg Fe eq	14.868
Fossil depletion	kg oil-eq	60.058

Note: Reported values correspond to the functional unit of 1000 kg of cement at the plant gate.

The climate change impact was calculated at 772.215 kg CO_2-eq per tonne of cement. This result lies within the range commonly cited in the LCA literature for Portland and Portland-composite cements, approximately 600–900 kg CO_2-eq per tonne, where the lower end is typically associated with reduced clinker factors, higher shares of alternative and biomass-derived fuels, and lower-carbon electricity mixes [1,2,22]. The present value falls in the upper-middle part of this interval. This is compatible with the modelled clinker content of 775 kg per tonne of cement (Section 2.2.2), which is lower than that of CEM I cements, for which reported climate change results cluster closer to the upper end of the range [9,22]. The pattern is consistent with comparative LCA studies of composite cements containing limestone and slag, which generally report climate change reductions that scale approximately with the degree of clinker substitution [5,10,16]. Because natural gas and packaging materials were not modelled, the result should be regarded as a product-stage estimate under the stated model limitations (Section 4.9).

Beyond climate change, the assessment yielded, for example, 60.058 kg oil-eq per tonne for fossil depletion, 14.868 kg Fe eq for metal depletion, 8.464 kg 1,4-DB eq for human toxicity, and 4.532 kBq U-235 eq for ionising radiation (Table 4). Because these midpoint

indicators are expressed in mutually incompatible units (mass equivalents of different reference substances, radioactivity equivalents, or volumetric quantities), their absolute values cannot be meaningfully ranked to establish an order of environmental importance. Such a comparison would require either normalisation (expressing each result relative to a regional or global per-capita reference value) or a full weighting and aggregation procedure at the endpoint level. Neither was undertaken in this midpoint-only assessment.

Water depletion returned a net value of −1085.755 m^3 per tonne of cement, which is not a physical water flow, and the category was excluded from the interpretation. The stage contributions of P2, P3, P6 and P8 each correspond to approximately −9.57 m^3 per kWh of allocated electricity (Tables S1 and S4), whereas the foreground water input (P1) and the fuel supply chains (P4) contribute less than 0.01%. The result therefore originates in the background Serbian electricity-market dataset (ecoinvent v3.1) as characterised by ReCiPe Midpoint (H) v1.11, not in the plant inventory. The value is given in Table S4 for transparency only.

The overall LCIA results (Table 4) serve as the aggregate baseline against which the contributions of the ten foreground stages (P1–P10) are examined in the following sections. An aggregate midpoint value does not show which stage is responsible for a reported burden, or whether the same stage dominates across categories. Section 3.2 therefore decomposes each result in Table 4 among stages P1–P10 to identify the principal hotspots of the modelled system.

3.2. Climate Change Impact

The modelled climate change impact of the representative CEM II/A-L 42.5 R cement was 772.215 kg CO_2-eq per tonne of cement, consistent with the aggregate result in Table 4. The contribution of each production stage is shown in Figure 1 and summarised in Table 5.

The stage-level disaggregation shows a strongly concentrated hotspot in the pyroprocessing stages. The rotary kiln (P6) was the dominant contributor, at 522.99 kg CO_2-eq/t (67.7% of the total), driven mainly by fuel combustion and clinker calcination. The preheater and partial calcination stage (P5) was second, at 119.35 kg CO_2-eq/t (15.5%), and cement grinding with additions (P8) was third, at 66.19 kg CO_2-eq/t (8.6%). Together, P6, P5 and P8 accounted for approximately 91.8% of the total. The other stages (P1–P4, P7, P9 and P10) jointly accounted for the remaining 8.2% (Table 5).

Because the electricity of the clinker cooler and cement storage was allocated to other stages, the shares of P6 and P8 include part of these burdens and should not be read as attributable solely to kiln operation or grinding. P5 and P6 together contributed approximately 83.2% of the total, so the pyroprocessing stages are the principal source of climate change impact in the modelled system. In the inventory, calcination CO_2 (399.2 kg/t cement, split between P5 and P6) and fossil fuel-combustion CO_2 (216.4 kg/t cement, P6) together account for about 80% of the result (Section 2.2.5). This agrees with the general finding that calcination and fuel combustion dominate the climate change profile of cement manufacture in most plant configurations [22,23]. Both flows are model estimates (Tier 3 and Tier 4) rather than plant measurements, so the ranking of P5 and P6 depends on these assumptions (Table S5). Adding P8 raises the share of the three principal stages to 91.8%. Although grinding is electricity-driven rather than thermochemical, its contribution is not negligible and should be included in decarbonisation planning.

The remaining stages (P1–P4, P7, P9 and P10) had a comparatively limited influence on the climate change result. This has a direct implication for prioritising decarbonisation measures. Interventions targeting the pyroprocessing stages, such as alternative-fuel substitution, kiln thermal-efficiency improvements, or clinker-substitution strategies that lower the clinker factor, are likely to yield substantially larger reductions than measures

confined to the lower-contribution stages. P8, although far smaller than the kiln, remains the third-largest contribution. Its electricity-driven emissions depend on the carbon intensity of the electricity mix and may therefore respond to decarbonisation differently than the fuel-driven emissions of P5 and P6. The stage-wise distribution established here is the basis for Section 3.3, which extends the disaggregation to the remaining midpoint categories to determine whether P5, P6 and P8 dominate consistently across the full environmental profile or whether different categories are driven by different stages.

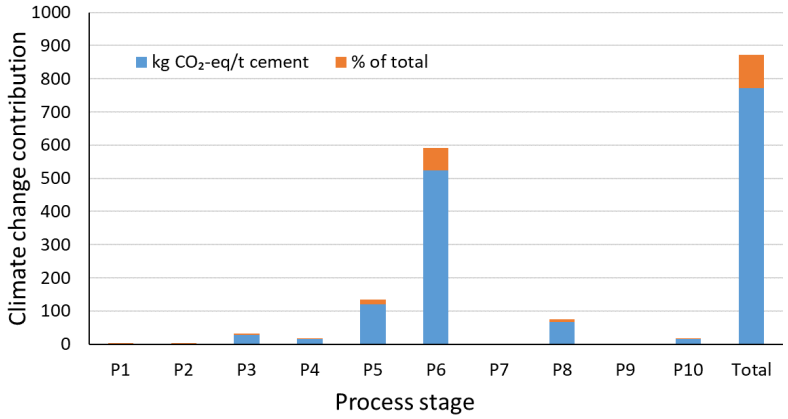


Figure 1. Climate change contribution of the ten foreground process stages (P1–P10) in cement production, expressed as kg CO_2-eq per tonne of cement.

Table 5. Stage-wise contribution of processes P1–P10 to the climate change impact category.

Code	Process	kg CO_2-eq/t Cement	% of Total
P1	Quarry extraction and preparation	2.24	0.29
P2	Crushing, transport and storage	1.14	0.15
P3	Raw material grinding and homogenisation	28.69	3.72
P4	Fuel storage, grinding and dosing	16.18	2.10
P5	Preheater and partial calcination	119.35	15.46
P6	Rotary kiln	522.99	67.73
P7	Clinker cooler	0.00 *	0.00 *
P8	Cement grinding with additions	66.19	8.57
P9	Cement storage	0.00 *	0.00 *
P10	Packing and plant-gate dispatch	15.43	2.00
	Total	772.215	100.0

* Zero values for P7 and P9 reflect the model structure and data availability described in Sections 2.2.4 and 2.2.9 (electricity use not sub-metered and allocated to other stages, mainly P6) and do not indicate an absence of physical burden. Stage values are rounded and may not sum exactly to the total.

3.3. Process-Level Environmental Hotspots

Section 3.2 showed that climate change is strongly concentrated in the pyroprocessing stages: P6 (67.7%) and P5 (15.5%) together contribute 83.2%, and 91.8% with P8 (Table 5). To establish whether P5, P6 and P8 also lead in the other midpoint categories, or whether different stages emerge as hotspots for specific indicators, Table 6 lists the category totals with the largest and second-largest stage contributions for all 18 ReCiPe midpoint categories. The full percentage contributions of P1–P10 for each category are given in Supplementary Table S4. The zero contributions of P7 and P9 reflect the model structure and data availability (Sections 2.2.4 and 2.2.9), not an absence of physical burden.

Table 6. ReCiPe Midpoint (H) v1.11 impact results for 1 tonne of modelled CEM II/A-L 42.5 R cement, with the dominant and second-largest production stage for each category.

Impact Category	Unit	Total Impact	Dominant Stage (Share, %)	Second-Largest Stage (Share, %)
Climate change	kg CO_2-eq	772.2154	P6—Rotary kiln (67.73)	P5—Preheater (15.46)
Ozone depletion	kg CFC-11-eq	9.575143×10^{-6}	P4—Fuel preparation (52.72)	P8—Cement grinding (21.67)
Terrestrial acidification	kg SO_2-eq	2.089818	P6—Rotary kiln (43.75)	P8—Cement grinding (26.67)
Freshwater eutrophication	kg P-eq	3.305466×10^{-2}	P8—Cement grinding (34.25)	P3—Raw material grinding (21.54)
Marine eutrophication	kg N-eq	5.223286×10^{-2}	P6—Rotary kiln (74.69)	P8—Cement grinding (11.59)
Human toxicity	kg 1,4-DB-eq	8.464320	P6—Rotary kiln (35.64)	P8—Cement grinding (34.38)
Photochemical oxidant formation	kg NMVOC	1.326942	P6—Rotary kiln (68.31)	P8—Cement grinding (16.18)
Particulate matter formation	kg PM_{10}-eq	0.815236	P6—Rotary kiln (37.66)	P8—Cement grinding (34.69)
Terrestrial ecotoxicity	kg 1,4-DB-eq	8.684765×10^{-3}	P6—Rotary kiln (43.40)	P8—Cement grinding (22.68)
Freshwater ecotoxicity	kg 1,4-DB-eq	7.734355×10^{-2}	P8—Cement grinding (32.55)	P4—Fuel preparation (19.14)
Marine ecotoxicity	kg 1,4-DB-eq	9.713585×10^{-2}	P6—Rotary kiln (36.26)	P8—Cement grinding (26.93)
Ionising radiation	kBq U-235-eq	4.532184	P4—Fuel preparation (40.76)	P8—Cement grinding (23.40)
Agricultural land occupation	$m^2 \cdot a$	1.537394	P8—Cement grinding (34.30)	P3—Raw material grinding (20.58)
Urban land occupation	$m^2 \cdot a$	0.973793	P4—Fuel preparation (56.35)	P8—Cement grinding (24.42)
Natural land transformation	m^2	2.305988×10^{-3}	P4—Fuel preparation (79.73)	P8—Cement grinding (11.86)
Water depletion (excluded from calculation)	m^3	−1085.755	P8—Cement grinding (36.91)	P3—Raw material grinding (24.78)
Metal depletion	kg Fe-eq	14.86775	P8—Cement grinding (97.83)	P3—Raw material grinding (0.76)
Fossil depletion	kg oil-eq	60.05828	P4—Fuel preparation (41.90)	P8—Cement grinding (25.31)

Note: P4 = fuel storage, grinding and dosing; P8 = clinker grinding with additions. The dominant stage is the one with the largest numerical share of the respective category total (Table S4). Natural land transformation has small negative contributions from P2, P6 and P10. Shares may not sum exactly to 100% because of rounding.

Table 6 shows that the dominance of the pyroprocessing stages seen for climate change does not hold across all midpoint categories (Figure 2).

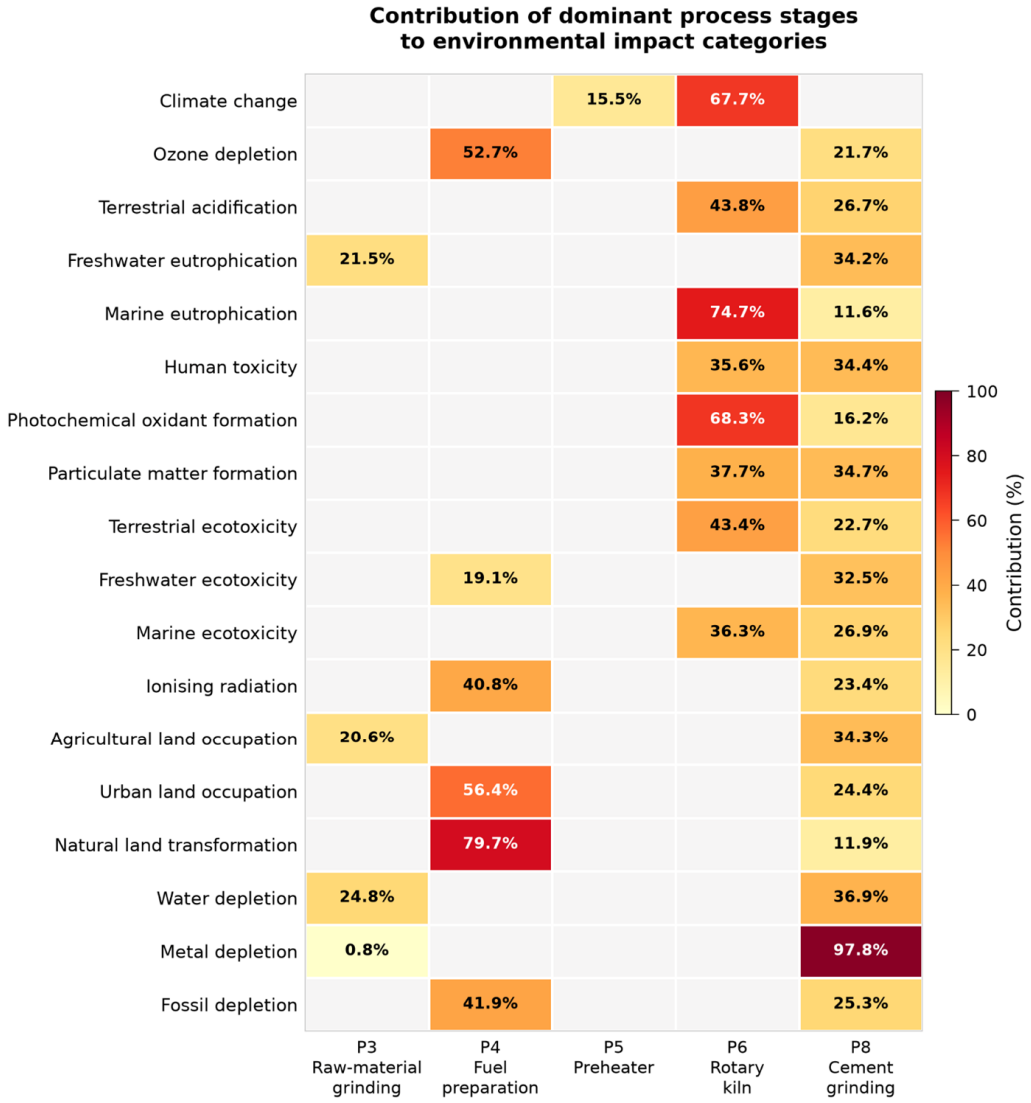


Figure 2. Heatmap of the relative contributions of selected process stages (P3–P6 and P8) across the 18 assessed midpoint impact categories. The heatmap highlights selected dominant contributions; complete process-stage results are provided in Supplementary Table S4.

The rotary kiln (P6) is the largest contributor in eight of the seventeen categories interpreted (water depletion being excluded; Section 3.1): climate change, terrestrial acidification, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity and marine ecotoxicity. This is consistent with its role as the most combustion- and calcination-intensive stage. In several of these, however, the lead is narrow: P6 exceeds P8 by only 1.3 percentage points for human toxicity and by 3.0 for particulate matter formation, so the two stages are effectively co-dominant there. Cement grinding with additions (P8) is the largest contributor for four categories: freshwater eutrophication, freshwater ecotoxicity, agricultural land occupation and metal depletion. P8 accounts for 97.83% of metal depletion. Because P3, which draws a comparable share of plant electricity, contributes only 0.76%, this hotspot most likely originates in the background datasets of the cement constituents rather than in grinding energy. The specific datasets responsible, including those of gypsum and slag, were not resolved in the present analysis and require verification (Section 4.4). Fuel storage, grinding and dosing (P4) is the largest contributor for five categories: ozone depletion, ionising radiation, urban land occupation, natural land transformation and fossil depletion. Because secondary fuels (SRF

and waste tyres) carry no upstream burden under the cut-off approach (Section 2.2), the P4 results reflect the upstream supply of petroleum coke and hard coal and would be expected to change under a different treatment of secondary fuels.

Supplementary Table S4 shows that P5 has a non-zero contribution only for climate change. The only quantified elementary flow of P5 is calcination CO_2 (Table S1), and no electricity or other inputs were entered for this stage. The absence of contributions in other categories therefore reflects the scope of the inventory, not an absence of other environmental flows (Section 4.9).

The divergence between categories has a direct methodological implication. A strategy focused only on the climate change hotspot would not address the hotspots for metal depletion, land use and several other indicators, which are concentrated in P8 and P4. The results indicate three principal stage clusters with different impact profiles: the pyroprocessing stages (P5–P6) for climate change and, through P6, several combustion- and process-related categories; cement grinding with additions (P8) for resource depletion and selected eutrophication, ecotoxicity and land-use categories; and fuel-related upstream processes (P4) for ozone depletion, ionising radiation, fossil depletion and land-use categories. The complete stage-by-category distribution is given in Supplementary Table S4.

3.4. Contribution to Other Environmental Impact Categories

The multi-impact results show that the environmental profile of the modelled cement system is not governed by a single production stage. Although the rotary kiln (P6) is the principal contributor to climate change (Table 5), its dominance is not universal. The leading stage in each category depends on the mechanism the midpoint indicator represents, as interpreted below from Tables 6 and S4.

The rotary kiln remains the largest contributor for terrestrial acidification, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity and marine ecotoxicity. This is plausibly linked to the measured stack emissions assigned to P6 in the inventory (NO_x, SO_2, NH_3, CO, TOC, particulates, HCl and metals; Table S1), together with kiln electricity. For human toxicity and particulate matter formation, the lead of P6 over P8 is narrow (35.6% vs. 34.4% and 37.7% vs. 34.7%, respectively), so these categories are better described as co-dominated by P6 and P8. Pyroprocessing therefore contributes substantially not only to greenhouse gas emissions but also to several atmospheric emission and toxicity categories.

A different pattern is seen for ozone depletion, ionising radiation, fossil depletion, urban land occupation and natural land transformation, for which fuel storage, grinding and dosing (P4) is the largest contributor, although its contribution to climate change is only 2.10% (Table 5). Because SRF and waste tyres carry no upstream burden under the cut-off approach, these results reflect the upstream supply of petroleum coke and hard coal. They illustrate why the complete fuel-supply chain, and not only direct kiln emissions, should be considered when evaluating cement production.

Cement grinding with additions (P8) is the largest contributor to freshwater eutrophication, freshwater ecotoxicity, agricultural land occupation and metal depletion, although it contributes only 8.6% of climate change. For freshwater eutrophication and agricultural land occupation, the shares of P3, P6, P8 and P10 are approximately proportional to the electricity allocated to each stage (Table S1). For example, for freshwater eutrophication, they are 21.5, 20.6, 34.3 and 11.8%, against 28.1, 26.9, 41.9 and 16.5 kWh/t cement. This suggests that these categories are largely driven by the background electricity dataset, and that P8 leads because it holds the largest electricity allocation (38%). Metal depletion is the exception: P8 accounts for approximately 97.8% of the impact, while P3, with a comparable electricity share, contributes only 0.76%. This points to the cement constituents rather than

to grinding energy (unverified; Section 4.4). These differences show that the significance of a stage cannot be inferred from its climate change contribution alone, in line with the caution in the LCA literature against using climate change as a proxy for overall environmental performance in cement and construction material assessments [15].

The results reveal three hotspot patterns, illustrated in Figure 3: P6 for climate change and a broad group of atmospheric and toxicity-related categories; P4 for fuel- and resource-related indicators (ozone depletion, ionising radiation, fossil depletion and land use); and P8 for electricity-related and aquatic environment indicators and, above all, metal depletion. A climate change-only assessment would correctly identify the kiln and preheater as the principal hotspots but would understate the stages that dominate other categories. When considering environmental improvement and decarbonisation measures for cement production, these findings support identifying hotspots category by category.

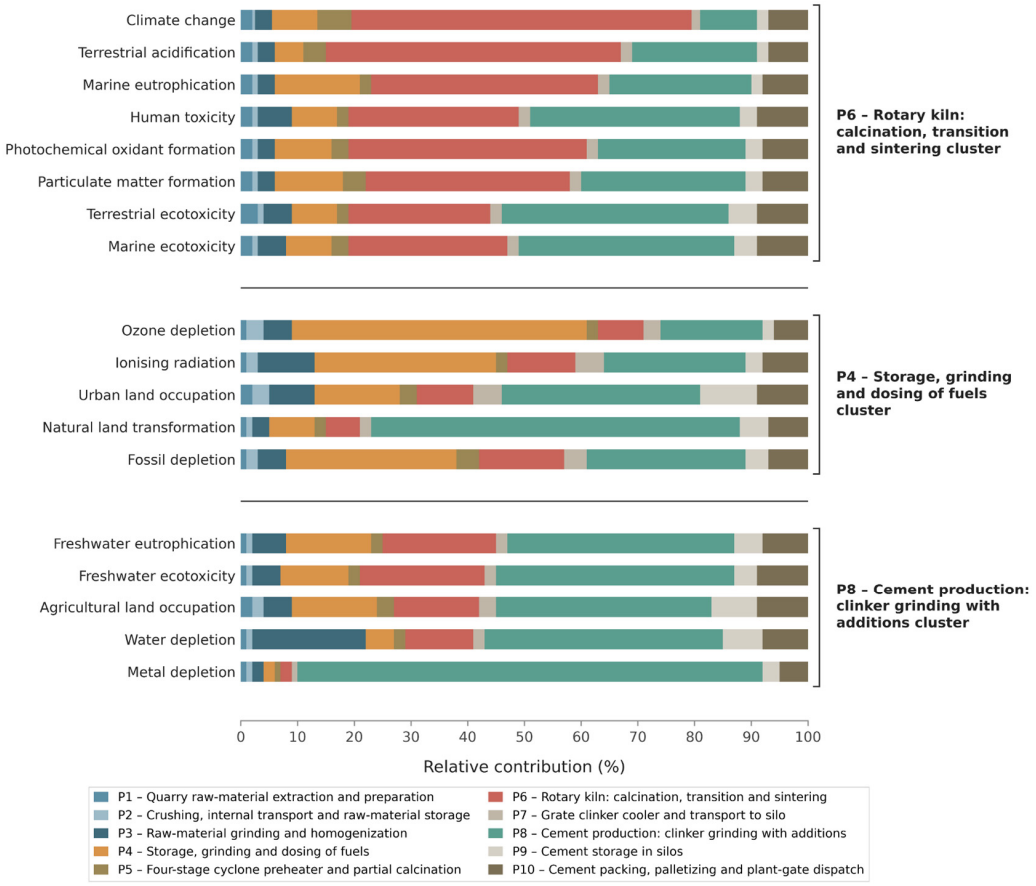


Figure 3. Clustering of the eighteen assessed midpoint impact categories by their dominant production stage (P6, P4 or P8). Human toxicity and particulate matter formation are co-dominated by P6 and P8; water depletion (P8) has a negative net value that arises from the background dataset and is not treated as a hotspot.

3.5. Uncertainty Analysis

The overall relative uncertainty of the climate change result was estimated at approximately ±11% (one standard deviation; Section 2.2.9, Table 2 and Supplementary Table S5). Coefficients of variation of 15–25% were assigned to the process-stage contributions according to data quality and propagated by variance-weighted summation, assuming independent contributions. The estimate addresses the uncertainty of the inventory data in the sense of the interpretation phase of ISO 14044 [18]. For the central estimate of 772.22 kg CO_2-eq/t cement, it corresponds to a one-standard-deviation interval of approximately 687–857 kg CO_2-eq/t cement (Figure 4). This is not a confidence interval.

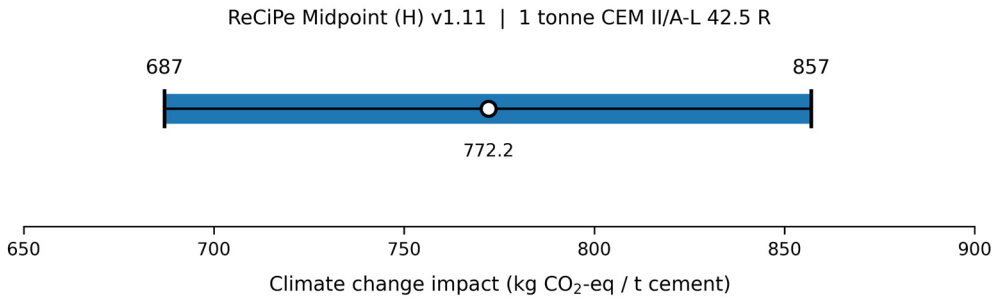


Figure 4. Central estimate of the climate change impact (772.22 kg CO_2-eq/t cement) with the associated ±11% (one standard deviation) uncertainty range (687–857 kg CO_2-eq/t cement).

Because the propagation is variance-weighted, the stages with the largest absolute contributions dominate the combined uncertainty. The rotary kiln (P6), at 522.99 kg CO_2-eq/t, accounts for the large majority of the propagated variance, at least about 80% within the assigned coefficient-of-variation range. Its inventory rests on estimated calcination-related and fuel-combustion CO_2, both based on modelling assumptions (Tiers 3 and 4; Section 2.2.5). Two of these assumptions are particularly influential. The assumed raw-meal loss on ignition (34%, BREF range 32–36%) determines total calcination-related CO_2 and by itself corresponds to approximately ±4–5% of the climate change result. The 30/70 split between P5 and P6 redistributes calcination-related CO_2 between the two stages, so it affects their individual values but not the total. These flows depend on shared assumptions, so their errors may be correlated, and the assumption of independent contributions may underestimate the combined uncertainty.

The ±11% estimate covers only the assigned data quality uncertainty of the stage contributions. Uncertainty from the background datasets, the LCIA method and the system boundary (for example, the omitted natural gas and packaging) was not quantified and is treated as a structural limitation (Section 4.9). The range should be regarded as a lower bound on the total uncertainty, and it should be considered when the absolute value is compared with results from other studies that use different system boundaries, datasets, allocation procedures or modelling assumptions.

The coefficients of variation were assigned to reflect differences in the data quality and uncertainty of the individual stage contributions (Supplementary Table S5). Independence was assumed in propagating these uncertainties because the available inventory data did not allow the correlations between all stage contributions to be quantified. This is a simplifying approximation, particularly for the preheater and rotary kiln, whose calcination-related CO_2 contributions depend on shared assumptions, so the calculated uncertainty may underestimate the combined uncertainty where correlations exist.

The estimated uncertainty does not alter the main interpretation of the process profile. The difference between P6 and the next-largest stage, P5, is 403.6 kg CO_2-eq/t, about five times the one-standard-deviation uncertainty of the total (±84.9 kg). This is consistent with the one-at-a-time ±30% perturbation (Table 7): even with P6 reduced by 30% and P5 increased by 30%, P6 remains the dominant stage. This indicates the robustness of the hotspot ranking under the specified perturbations, but it does not independently validate the emission estimates or eliminate uncertainty from the underlying assumptions. These findings apply to the investigated production scenario and system boundary. The interpretation of the absolute impact values is subject to the inventory and model limitations discussed in Sections 4.7 and 4.9. Within these limitations, the uncertainty and sensitivity analyses support the identification of the rotary kiln as the principal climate change hotspot.

Table 7. Sensitivity of the total climate change impact to a ±30% variation in individual process-stage contributions.

Stage	Baseline Contribution (kg CO_2-eq/t Cement)	Baseline Share (%)	Change in Total Climate Change Impact for ±30% Variation (%)
P1—Quarry extraction and preparation	2.24	0.29	±0.09
P2—Crushing, transport and storage	1.14	0.15	±0.05
P3—Raw material grinding and homogenisation	28.69	3.72	±1.12
P4—Fuel storage, grinding and dosing	16.18	2.10	±0.63
P5—Preheater and partial calcination	119.35	15.46	±4.64
P6—Rotary kiln	522.99	67.73	±20.32
P7—Clinker cooler	0.00	0.00	±0.00
P8—Cement grinding with additions	66.19	8.57	±2.57
P9—Cement storage	0.00	0.00	±0.00
P10—Packing and plant-gate dispatch	15.43	2.00	±0.60

Note: Values represent the change in the total climate change result caused by an independent ±30% perturbation of the contribution assigned to each stage, with all other contributions held constant. The analysis is a local, contribution-based sensitivity assessment and not a probabilistic uncertainty analysis. As in Table 5, the zero values for P7 and P9 reflect the model structure and data availability (Sections 2.2.4 and 2.2.9) and not an assumption of zero physical burden.

3.6. Sensitivity Analysis

The sensitivity analysis examines how strongly the total climate change result responds to changes in the contributions of individual process stages. The contribution of each stage was varied by ±30% while all other contributions were kept unchanged, and the resulting change in the total was expressed as a percentage of the baseline total (Section 2.2.9). This is a local, one-at-a-time, contribution-based approach, not a probabilistic treatment, and it complements the variance-weighted analysis in Section 3.5 [27]. The ±30% range is deliberately wider than the coefficients of variation of 15–25% assigned in Section 3.5, so that it acts as a bounding case. Hence, the perturbation is applied to stage contributions and not to their underlying inputs; the change in the total equals the baseline share multiplied by 0.30 by construction (Table 7). The analysis thereby expresses the contribution ranking as a measure of leverage and is not an independent test of the hotspot identification.

The rotary kiln (P6) showed by far the highest sensitivity. With a baseline contribution of 522.99 kg CO_2-eq/t cement (67.73% of the total), a ±30% variation in its contribution changed the total by approximately ±20.32%. The next most influential stages were the preheater and partial calcination stage (P5), at 15.46% of the total and a ±4.64% change, followed by cement grinding with additions (P8), with ±2.57%. Raw material grinding and homogenisation (P3) and fuel storage, grinding and dosing (P4) produced substantially smaller changes of approximately ±1.12% and ±0.63%, while packing and plant-gate dispatch (P10), quarry extraction (P1) and crushing, transport and storage (P2) had only

marginal effects of ±0.60%, ±0.09% and ±0.05% (Figure 5). The resulting ranking was P6 > P5 > P8 > P3 > P4 > P10 > P1 > P2. For the clinker cooler (P7) and cement storage (P9), a proportional perturbation of a zero contribution has no effect, so their sensitivity cannot be assessed. As explained in Sections 2.2.4 and 2.2.9, this reflects model structure and data availability, not the absence of physical burden.

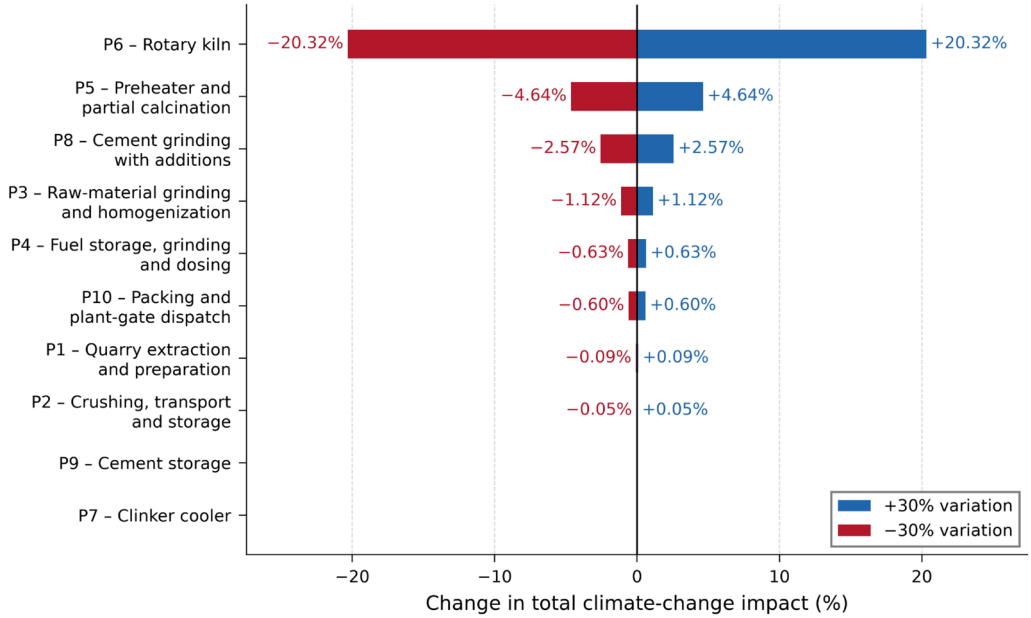


Figure 5. Sensitivity of the total climate change impact to a ±30% variation in the contribution of each process stage (P1–P10): change in the total resulting from an independent ±30% perturbation of each stage's baseline contribution.

A ±30% change in P6 alters the total by more than four times as much as the same relative change in P5 and by almost eight times as much as in P8. Since the ranking follows directly from the baseline shares, a more informative question is how large a change would be needed to alter it. P5 would exceed P6 only if P6 decreased and P5 increased by about 63% simultaneously, and P8 would exceed P6 only for opposite changes of about 78%, both well outside the ±30% range examined. Reductions in kiln-related emissions would therefore have a substantially greater influence on the overall climate change impact than equivalent relative reductions in any other single stage.

These results are consistent with the contribution analysis in Sections 3.2 and 3.3, in which P6 was identified as the principal climate change hotspot. They indicate where changes would have the greatest leverage, namely kiln efficiency, fuel consumption, clinker-production efficiency and process-related emissions. They do not test the assumptions behind the P5 and P6 inventories (raw-meal loss on ignition, calcination split, fuel-combustion CO_2), which remain a source of uncertainty (Section 3.5). Uncertainty and sensitivity assumptions are given in Supplementary Table S5.

4. Discussion

4.1. Dominance of the Clinker-Production Chain

The concentration of the climate change burden in the clinker-production chain (P3–P7, 89.0% of the total) is not merely a numerical artefact of the present model. It is consistent with the thermochemical characteristics of Portland-composite cement manufacture. Clinker production combines two co-located sources of greenhouse gas emissions: the calcination of carbonate-bearing raw materials, a process-related CO_2 source governed by

the chemistry of the raw meal rather than by equipment efficiency, and the combustion of the fuel required to sustain the temperatures at which calcination, clinker-mineral formation and sintering occur. This dual origin is why the pyroprocessing stages consistently emerge as the dominant climate change hotspot in the LCA literature [22,23]. In the modelled system, the rotary kiln (P6) was the principal contributor, at 67.7% of the total, and the preheater and partial calcination stage (P5) contributed a further 15.5%. These two stages accounted for approximately 83.2% of the climate change impact, a proportion comparable to the pyroprocessing shares reported in other stage-resolved cement LCAs under different system boundaries [22,23]. Calcination CO_2 and fossil fuel-combustion CO_2 account for about 80% of the result (Section 2.2.5).

The high contribution of P6 reflects the central role of the rotary kiln in clinker formation. The kiln is where the raw meal reaches the highest process temperatures and where the sintering reactions produce the principal clinker minerals (alite, belite, aluminate and ferrite phases). In the model, P6 therefore carries the largest fuel demand, since all fuel-combustion CO_2 is assigned to it, together with 70% of the calcination CO_2. P5 contributes because the preheater and precalciner begin the decomposition of the raw meal upstream of the kiln and is represented by its 30% share of calcination CO_2. The 30/70 split between the two stages and the assignment of all fuel combustion to P6 are modelling assumptions, not plant measurements (Table S1; Section 3.5). The individual values of P5 and P6 should therefore be read with caution, whereas their combined share is the more robust result.

These results indicate that the main opportunities for reducing the climate change impact of the modelled system lie predominantly in the pyroprocessing stages. Measures targeting kiln thermal efficiency, fuel-mix decarbonisation (including alternative, waste-derived and biomass fuels), precalciner optimisation and, at a more structural level, reduction of the clinker factor through increased use of supplementary cementitious materials are expected to yield larger reductions than equivalent relative improvements in the lower-contribution stages. Two accounting conventions in the model should be kept in mind when interpreting the benefit of fuel substitution: secondary fuels (SRF and waste tyres) carry no upstream burden under the cut-off approach, and biogenic CO_2 is reported separately from fossil CO_2 (Table S1). These conventions may limit the extent to which trade-offs of alternative-fuel use are captured. Similarly, although clinker substitution can reduce climate change impacts, the overall benefit depends on the burdens of the substitute materials, which may be underestimated when they carry no upstream burdens under the cut-off approach. This interpretation is consistent with the leverage analysis in Section 3.6, in which a ±30% perturbation of the P6 contribution alone changed the total by approximately ±20.3%, more than four times the effect for P5 and almost eight times that for P8. Because the perturbation is proportional to the baseline share by construction, this asymmetry expresses leverage and not an independent test. It nevertheless shows that the kiln is not only the largest contributor but also the stage where a given relative change matters most for the total, which is relevant when prioritising limited decarbonisation investment. The ranking remains unchanged within the estimated uncertainty of the result (Section 3.5).

The predominance of P6 should not be read as evidence that the remaining stages are environmentally insignificant or that they can be deprioritised across the full scope of environmental concern. It is specific to the climate change indicator. As Sections 3.3 and 3.4 show, the dominant stage shifts once other midpoint categories are considered, with fuel preparation (P4) and cement grinding (P8) each leading several non-climate indicators. The conclusion of this section is therefore narrower but no less important. For climate change, and for the categories in which P6 is also strongly dominant (marine eutrophication, photochemical oxidant formation and, to a lesser extent, terrestrial acidification; Table 6), the concentration of impacts in P6 shows that decarbonisation efforts focused

on the pyroprocessing stages are likely to provide the greatest benefit within the defined system boundary.

4.2. Role of the Preheater and Partial Calcination

The contribution of P5, 15.5% of the total climate change impact, shows that the preheater and partial calcination stage should not be regarded as a merely auxiliary operation. Preheating and partial calcination are an integral part of the thermal system responsible for clinker production, and in a preheater/precalciner configuration, the raw meal has already undergone part of its calcination before it reaches the kiln. This is consistent with stage-resolved LCA studies that treat the preheater tower as a distinct contributor to the pyroprocessing burden and do not fold it into the kiln result [22,23]. In the present model, P5 is represented only by its share of calcination CO_2, and no electricity or fuel was assigned to it (Table S1). If the plant operates a precalciner, a larger share of calcination would occur in P5 than the assumed 30%.

The separate representation of P5 and P6 is a modelling choice that affects how the results should be read. The 30/70 distribution of calcination CO_2 between the two stages and the assignment of all fuel-combustion CO_2 to P6 are assumptions, not plant measurements (Section 3.5). The difference between P5 and P6 (15.5% versus 67.7%) therefore reflects the internal accounting of the model and not a physical separation of emissions, since the two stages are phases of a single continuous thermal process. Their combined contribution, approximately 83.2%, is the more robust figure for the importance of the pyroprocessing stages because it is insensitive to how emissions are apportioned between them, although it still depends on the total calcination CO_2 and thus on the assumed raw-meal loss on ignition.

This has consequences for comparison with other LCA studies. Studies adopt different process-stage definitions and different conventions for allocating calcination-related emissions between preheater and kiln [2,15,35,36]. Some report a single aggregated pyroprocessing or clinker-burning stage, while others, as here, separate preheating from the kiln. Where the internal boundary is drawn can substantially change the contribution assigned to individual unit processes: a 15.5% versus 67.7% split in one study might correspond to a very different boundary in another, without any real difference in the importance of clinker production as a whole. The P5/P6 split reported here should therefore be treated as internally consistent within the present model, not as a value directly transferable to studies with different boundary conventions. The combined P5 + P6 figure is the more appropriate basis for cross-study comparison.

4.3. Influence of the Modelled Clinker Content

The modelled LCA scenario adopts 775 kg of clinker per tonne of cement (Section 2.2.2). On the EN 197-1 basis, this corresponds to 81.0% clinker, close to the lower bound of the 80–94% range for CEM II/A-L. The composition also contains 48 kg of granulated blast-furnace slag and is therefore not a strict CEM II/A-L formulation (Section 2.2.2). This value is the clinker quantity used to scale the investigated scenario and should not be interpreted as a generalised composition for all cements marketed under the CEM II/A-L 42.5 R designation, for which the standard permits a range of clinker content. The climate change impact reported in Section 3.1 is specific to the modelled clinker-to-cement ratio and its process inventory. Two cements with the same label may differ meaningfully in clinker content within the permitted range, and therefore in climate change performance, so environmental performance should be interpreted in relation to actual, plant-specific clinker content and not the standardised designation alone.

Clinker content is arguably the most consequential compositional parameter in the assessment, because the clinker-production stages account for the large majority of the

climate change impact (Sections 3.2 and 4.1). Since the clinker-related stages scale with the clinker requirement (Section 2.2.6), the effect is roughly linear: on the basis of Table 5, each 10 kg/t change in clinker content corresponds to approximately 9 kg CO_2-eq/t cement, or about 1.2% of the result. This is a first-order estimate that assumes constant stage intensity and a negligible burden of the substituting constituent. Under the cut-off approach, slag carries no upstream burden, so it is an upper bound for slag substitution. The finding is consistent with comparative LCA studies of composite cements, which generally report climate change reductions that scale closely with the degree of clinker substitution by limestone, slag, fly ash or other constituents [5,10,16].

Two complementary decarbonisation strategies can be distinguished. The first is process efficiency: improving the emissions performance of clinker production through kiln thermal-efficiency improvements, waste-heat recovery, fuel substitution toward lower-carbon or biomass-derived alternatives [12–14] and precalciner optimisation. The second is product formulation: reducing the clinker required per tonne of cement by incorporating supplementary cementitious constituents, provided that the cement continues to meet the mechanical, durability and regulatory requirements [29]. The two strategies address different points of the system: the emissions of each unit of clinker and the amount of clinker required, and are complementary rather than mutually exclusive. In this model, calcination CO_2 (399.2 kg/t cement, about 52% of the total climate change impact) can be lowered by reducing the clinker content or changing the raw materials, but not by kiln efficiency. Combining both strategies would give larger reductions than either alone, although not their arithmetic sum, because their effects multiply. This is broadly consistent with recent multi-lever assessments of decarbonisation in the cement sector [37,38].

A consistent functional basis is required whenever cement products or LCA studies are compared. A cement with a lower clinker content may report a lower climate change impact per tonne mainly because less clinker was produced per tonne of product, which is a compositional effect. Differences in the efficiency with which the clinker was produced are a separate, operational effect. Conflating the two risks misattributing a compositional advantage to an operational one, or vice versa, an interpretive error noted in comparative cement LCA reporting [2,15]. Meaningful comparisons should therefore consider product composition, clinker content, process efficiency, the type and proportion of supplementary constituents, and system boundaries together. The result reported here is representative of the investigated production scenario and its clinker-to-cement ratio, not a universal value for CEM II/A-L 42.5 R as a product category.

4.4. Importance of Cement Grinding

Cement grinding with additions (P8) contributes 66.19 kg CO_2-eq/t cement, 8.6% of the total climate change impact and the third-largest single-stage contribution, behind only the kiln and the preheater. Although this is substantially lower than the contribution of the two pyroprocessing stages (Sections 4.1 and 4.2), P8 becomes the dominant stage for several other impact categories, most strikingly metal depletion, where it accounts for approximately 97.8% of the total (Table 6). This shows that the environmental significance of grinding extends beyond greenhouse gas emissions and cannot be inferred, or dismissed, from its climate change share alone.

The contribution of P8 also highlights the electricity demand of clinker grinding, since finish grinding is well documented as one of the most electricity-intensive operations in cement production [23]. The resulting impacts depend on the electricity consumed and on several interacting factors: grinding technology, the efficiency of milling and classification equipment, the carbon and resource intensity of the electricity supply, and the way plant electricity is distributed among process stages. In the present model, the electricity of

P8 (41.9 kWh/t cement) was derived from a plant-stated 38% share of total electricity (Table S1). Improvements in grinding efficiency, whether through equipment upgrades, process optimisation or less energy-intensive milling technologies, can therefore contribute meaningfully to impact reduction even where their effect on the climate change result is smaller than that of measures targeting clinker production directly.

The contribution of P8 to metal depletion (approximately 97.8%) should be regarded as an unverified outcome of the background datasets. It cannot be attributed to electricity use, because P2, P3, P6 and P10 draw electricity at a comparable rate yet show only about 0.004 kg Fe-eq per kWh, and the limestone dataset used in P8 also appears in P3 without a corresponding contribution (Tables S1 and S4). The result therefore most likely originates in the datasets of the gypsum or slag constituents. The linkage of these datasets could not be resolved from the exported results, and a flow-level contribution analysis is required to confirm whether they are connected to metallurgical or iron-related processes. Until this has been done, the P8 metal-depletion hotspot should be read as a feature of the background data and not as evidence of an impact of grinding. It nevertheless illustrates that hotspots identified through climate change alone may differ from those in other categories, although in this case the identity of the hotspot is conditional on verification of the constituent datasets.

From a process-improvement perspective, these results support attention to energy-efficient grinding systems, optimisation of grinding practices and, where feasible, lower-carbon electricity for the grinding stage. The benefit of such measures should be evaluated across the relevant impact categories and not against climate change alone. A change in electricity sourcing that lowers the climate change contribution of P8 would not necessarily reduce its metal-depletion burden, which in the model is governed by the cement constituents and not by the carbon intensity of the electricity grid. Cement grinding should therefore be regarded as an important secondary hotspot, whose relative importance ranges from 8.6% of climate change to 97.8% of metal depletion.

4.5. Implications for Environmental Improvement

The results in Sections 3 and 4.1, Sections 4.2–4.4 indicate that the clinker-production system is the primary target for reducing the environmental burden of the modelled cement, particularly, though not exclusively, with respect to climate change. The dominant contribution of the rotary kiln, together with the substantial contribution of the preheater and partial calcination stage, indicates that improvements in thermal efficiency, fuel consumption and fuel-mix decarbonisation, precalciner optimisation and, for process-related emissions, reduction of the clinker factor (Section 4.3) or carbon capture are likely to provide the greatest reductions in climate change impact within the modelled system boundary. The leverage analysis in Section 3.6 points in the same direction, although, as noted there, it follows from the baseline shares by construction.

The multi-impact assessment also shows that environmental improvement in cement manufacture cannot be reduced to CO_2 mitigation alone, in line with calls in the LCA literature for decarbonisation strategies to be evaluated against a broader set of indicators [2,15]. The rotary kiln, the stage with the highest climate change impact, was not the dominant contributor in every category. Fuel storage, grinding and dosing (P4) and cement grinding (P8) led several other categories (Table 6). Measures directed at electricity consumption, electricity sourcing and the cement constituents of P8 (Section 4.4) should therefore be pursued alongside, and not after, measures targeting the kiln. Interventions designed to reduce greenhouse gas emissions, such as carbon capture retrofits at the kiln [38] or extensive fuel-switching programmes [12–14,37], should likewise be evaluated for their potential to shift burdens to other categories and not be assumed to deliver uniform benefits

across the environmental profile. A capture technology with a substantial parasitic energy demand, for instance, could plausibly increase fuel- and electricity-linked burdens (P4 and P8) while reducing the direct CO_2 emissions of P6. In the present model, burden-shifting from alternative fuels cannot be detected, because SRF and waste tyres carry no upstream burden under the cut-off approach, so any such shift would be understated (Table S1).

The results thereby support a hierarchical but integrated approach to environmental improvement. Priority should first be given to the major pyroprocessing hotspots, P5 and P6, because of their dominant contribution to climate change, the category widely regarded as the principal environmental concern for cement manufacture. At the same time, the secondary hotspots identified through the multi-impact assessment, principally P8 for resource- and aquatic-environment indicators and P4 for fuel-related upstream burdens, should be addressed concurrently and not deferred, so as to avoid a burden-shifting outcome in which climate-focused investment leaves, or even worsens, performance for metal depletion, freshwater eutrophication and ecotoxicity, or fossil-resource use.

The combination of contribution, sensitivity and uncertainty analysis provides a more informative basis for prioritising improvement opportunities than the total climate change result alone. Contribution analysis identifies where in the production system the impacts arise. Sensitivity analysis (Section 3.6) indicates which stages have the greatest leverage over the modelled result. Uncertainty analysis (Section 3.5), consistent with uncertainty treatments in the building-materials LCA literature [27], indicates the confidence that can be placed in the calculated values. Since the estimated ±11% covers only the assigned data quality uncertainty and is a lower bound (Section 3.5), it supports the ranking of stages but not fine distinctions between them. These analyses allow improvement measures to be prioritised according to both their potential benefit and the robustness of the evidence, a combination that a single aggregate score cannot provide.

4.6. Benchmarking Against Published Cement LCA/EPD Results

The calculated climate change impact of 772.22 kg CO_2-eq per tonne of cement provides a useful, if cautious, reference point for comparison with published assessments of comparable CEM II/A-L cements. Such comparisons must be approached carefully because reported greenhouse gas emissions for nominally similar cements depend on many methodological and technological parameters that are rarely harmonised across sources: clinker content, fuel mix, electricity-supply carbon intensity, geographical context, co-product allocation, the vintage and provenance of background datasets, and the system boundary. This is a recurring finding in the LCA-comparability literature, which cautions against treating cement LCA and EPD figures as interchangeable without first confirming that these parameters are aligned [2,15].

Published environmental product declarations (EPDs) illustrate this variability directly. Table 8 lists two publicly available EPDs for CEM II/A-L 42.5 R cement issued by the same manufacturer for two Spanish plants. They were selected because they declare a climate change result for modules A1–A3 under a defined system boundary and share the cement type and strength class of the present study. The GlobalEPD declaration for the Olazagutía plant of Grupo Cementos Portland Valderrivas reports 809.00 kg CO_2-eq/t for modules A1–A3 [39], and the Mataporquera plant reports 719.27 kg CO_2-eq/t (net A1–A3 value) [40].

Table 8. Contextual comparison of the calculated climate change impact with published Environmental Product Declarations for comparable Portland-limestone cements.

Source/Product	Cement Type	Clinker Content	System Boundary	Climate Change Impact (kg CO_2-eq/t Cement)	Methodological Context
Present study	CEM II/A-L 42.5 R	775 kg/t (81.0% of main and minor constituents)	Cradle-to-gate; plant gate	772.22	ReCiPe Midpoint (H) v1.11; process-level SimaPro model
Grupo Cementos Portland Valderrivas, Olazagutía—GlobalEPD EN 16908-078	CEM II/A-L 42.5 R	80–94% (EN 197-1 range; not disclosed as kg/t)	A1–A3	809.00	GlobalEPD/EN 15804 framework
Grupo Cementos Portland Valderrivas, Mataporquera—GlobalEPD EN 16908-104	CEM II/A-L 42.5 R	80–94% (EN 197-1 range; not disclosed as kg/t)	A1–A3	719.27 (net)	GlobalEPD/EN 15804 framework

Note: Values are presented for contextual benchmarking only and should not be interpreted as a product ranking. Differences in clinker content, fuel mix, electricity supply, background datasets, allocation procedures, impact-assessment methodology, geographical scope and system-boundary definitions can substantially influence reported results. The present study applies ReCiPe Midpoint (H) v1.11, whereas the cited EPDs apply EN 15804-based environmental indicators [20,21]; direct numerical comparison should therefore be made with caution.

The present result of 772.22 kg CO_2-eq/t lies between the two plant-level values, 36.8 kg below Olazagutía and 53.0 kg above Mataporquera. Even for two plants of the same company producing a cement with the same designation (CEM II/A-L 42.5 R, EN 197-1), the declared values differ by approximately 90 kg CO_2-eq/t. This spread is likely to reflect differences in fuel mix, raw materials, transport distances and process conditions, although neither declaration discloses enough process-level detail (fuel-mix proportions, electricity-grid composition, allocation approach) to confirm this. The present value should therefore be interpreted as a benchmark for the modelled production scenario in Section 2, not as evidence of superior or inferior performance relative to any commercial product in Table 8.

The calculated value is thus consistent with the interval spanned by the two EPDs and with the literature range discussed in Section 3.1, which supports its plausibility and order of magnitude. Two features of the present model should be kept in mind. Climate change is characterised here with IPCC 2007 GWP100 within ReCiPe, whereas EPDs use their own indicator set and treatment of biogenic carbon. In addition, natural gas and packaging were not modelled (Section 2.2.3), so the value may be lower than a complete A1–A3 figure (Section 4.9). A like-for-like comparison would require harmonising the clinker-to-cement ratio, electricity mix, fuel composition, allocation procedure, background dataset and system boundary, which EPD summary figures do not always allow [20,21]. Neither GlobalEPD declaration discloses clinker content in kg/t, only the EN 197-1 range of 80–94%, which limits the comparison and supports the point in Section 4.3 that products should be compared on their actual clinker content.

Published LCA and EPD results are therefore used here as contextual benchmarks that establish plausibility, not as a basis for product ranking or comparative claims. The comparison also reinforces a point made throughout this Discussion: the cement-type designation alone is an insufficient basis for inferring environmental performance, and reporting the underlying inventory assumptions, clinker content foremost among them, alongside the impact value is essential if published results are to support meaningful comparison, as the sector's decarbonisation reporting increasingly requires [16].

4.7. Data Quality, Uncertainty and Sensitivity

The reliability of the process-level life cycle assessment depends not only on the selected impact assessment method, ReCiPe Midpoint (H) v1.11, but also on the quality, representativeness and level of detail of the underlying life-cycle inventory. In accordance with the interpretation principles of ISO 14044 [18], the results should therefore be considered in relation to the completeness and quality of the inventory data, the assumptions used to estimate individual flows, and the extent to which uncertainty could be evaluated.

An important limitation of the present assessment is that not all emission flows were determined from direct plant measurements. Calcination-related CO_2 and fuel-combustion CO_2 associated with clinker production were estimated using the assumptions described in Section 2.2.5, as sufficiently detailed measurements were not available at the required process-stage resolution. Consequently, the absolute impact values depend partly on these assumptions. The estimates enable a process-level assessment but should not be interpreted as equivalent to directly measured emission data.

The quantitative uncertainty estimate and the influence of the main inventory assumptions are presented in Section 3.5. The estimated ±11% uncertainty reflects only the assigned data quality uncertainty of the process-stage contributions; it is not a confidence interval and does not represent a comprehensive quantification of all uncertainty sources. Uncertainty associated with background datasets, the life-cycle impact assessment method and structural aspects of the system model was not quantified. These limitations include the use of a single Serbian electricity-market dataset from ecoinvent v3.1 (2014), as well as omissions and data-resolution constraints discussed in Section 4.9. The estimate should therefore be interpreted as a partial assessment, with additional sources of uncertainty remaining unquantified.

This applies particularly to the rotary kiln stage (P6). Although a coefficient of variation of 15% was assigned in the data quality assessment, this value does not fully capture the additional uncertainty arising from estimating calcination-related and fuel-combustion CO_2 emissions without sufficiently detailed direct measurements. The reported ±11% may therefore understate the uncertainty of the P6 inventory and should be read as the uncertainty quantified under the adopted data quality assumptions, rather than as a comprehensive measure of kiln-related uncertainty.

The contribution and sensitivity analyses identify the rotary kiln as the dominant contributor to climate change within the investigated production system. This finding concerns the relative importance of the process stages under the specified modelling assumptions and should be distinguished from the uncertainty affecting the absolute impact values. The sensitivity analysis is a deterministic, one-at-a-time perturbation of stage contributions and does not independently validate the underlying emission estimates.

Future assessments would benefit from more detailed plant-specific measurements, particularly of raw-meal properties, fuel consumption and composition, and process-related emissions. Improved stage-specific monitoring and more detailed allocation of energy and material flows would reduce dependence on assumptions and support a more comprehensive uncertainty assessment. Such improvements are particularly important when comparing absolute impact values across plants with different operating conditions and data sources.

4.8. Implications for Environmental Improvement and Decarbonisation

The process-contribution analysis in Section 3, interpreted in Sections 4.1–4.7, gives a defensible basis for identifying improvement pathways within the modelled cement-production system. For climate change, the contribution analysis, supported by the leverage and uncertainty analyses (Sections 3.5 and 3.6), indicates that the greatest reduction poten-

tial lies in the pyro-processing stages: the rotary kiln and the preheater/partial calcination stage. Measures targeting kiln thermal efficiency, reduction of radiative and convective heat losses, optimisation of combustion and clinker-burning conditions, and substitution of fossil fuels with lower-carbon or biomass-derived alternatives [12–14] are therefore expected to have the greatest influence on the fuel-related share of the climate change result. This agrees with sector-wide decarbonisation assessments that identify the same intervention cluster as the highest-priority near-term lever [37,38]. Kiln-side measures do not remove the process CO_2 released by calcination (399.2 kg/t cement in the model, Section 4.3), which can only be lowered by a smaller clinker requirement or by capturing the CO_2.

A complementary and structurally distinct pathway is the reduction of clinker content per tonne of cement, provided that the product still meets the applicable technical and regulatory requirements [29]. Since clinker production is the dominant source of climate change impact in the modelled system (Sections 4.1–4.3), lowering the clinker mass reduces the associated process and energy burdens approximately in proportion (about 9 kg CO_2-eq/t cement per 10 kg/t of clinker, Section 4.3), in line with the scaling reported for composite cements [5,10,16]. The benefit should be evaluated jointly with the impacts of producing, processing and transporting the substitute materials. Supplementary cementitious materials are rarely burden-free and can introduce impacts in categories other than climate change. In the present model, granulated blast-furnace slag carries no upstream burden under the cut-off approach, so the benefit of slag substitution is an upper bound.

Improvements to the preheater and calcination system are also relevant. Improved heat recovery from kiln exhaust gases, reduced thermal losses in the preheater tower and optimised heat transfer and calcination conditions in the precalciner can complement improvements within the rotary kiln, reinforcing the point in Section 4.2 that P5 and P6 form a continuous thermal system rather than independently optimisable units. The model, however, represents P5 only through its share of calcination CO_2 and assigns no fuel or electricity to it (Table S1). The effect of such measures would therefore appear mainly as reduced fuel use in P6, and the present model cannot resolve it stage by stage.

Cement grinding contributes much less to climate change than clinker production, but it is the largest contributor to several other categories (Section 4.4). Grinding efficiency and electricity consumption should thus be part of any comprehensive improvement strategy. Reducing specific electricity consumption, improving milling and classification efficiency, optimising grinding-media selection and wear management [41] (a real-world measure not represented in the present inventory) and sourcing lower-impact electricity may each provide additional benefit. The magnitude, and direction, of these effects should be evaluated across the impact categories in which P8 is influential rather than inferred from the climate change contribution alone, given the divergence between P8's climate change share (8.6%) and its metal-depletion share (97.8%) (Table 6). The wider argument for a combined rather than sequential strategy, and the risk of burden-shifting between categories, is discussed in Section 4.5.

Finally, improved process monitoring and inventory resolution are an enabling rather than a directly emission-reducing measure, but an important one. More accurate stage-level measurement (Section 4.7) would allow hotspots to be identified with greater confidence and provide a stronger basis for evaluating the effects of any process modification. These priorities derive from the modelled process contributions in Section 3. In line with the qualifications in Section 4.3, they should be interpreted as potential improvement pathways specific to the investigated production scenario, not as prescriptive recommendations applicable without adaptation to any particular cement plant.

4.9. Limitations and Future Work

Several limitations should be considered when interpreting the results.

(1) Key inventory assumptions. The two largest CO_2 flows in the inventory are estimated rather than based entirely on direct plant measurements: calcination-related CO_2, calculated using an assumed raw-meal loss on ignition of 34% (BREF range 32–36%) and allocated 30/70 between P5 and P6, and fuel-combustion CO_2, estimated from the fuel mix, fuel-specific calorific values and IPCC default emission factors (Section 2.2.5, Table S1). These flows together account for about 80% of the climate change result. The assumed LoI alone corresponds to approximately ±4–5% of the result, whereas the 30/70 allocation affects the individual stage contributions but not the total calcination-related emissions (Section 3.5). These assumptions therefore affect the absolute climate change result and the distribution of calcination-related emissions between P5 and P6. Their quantitative implications are presented in Section 3.5, and the broader implications for data quality and interpretation are discussed in Section 4.7. Future assessments should prioritise plant-specific measurements of raw-meal properties, fuel consumption and composition, and process emissions.

(2) Model structure and data availability. The clinker cooler (P7) and cement storage (P9) show zero impacts because their electricity consumption was not separately metered and was allocated to other stages, mainly P6, according to plant-provided allocation shares. These zero values therefore reflect the inventory structure and data availability, not an absence of physical environmental burdens. Their only quantified flows are links to the preceding stage and, for P7, a capacity-based particulate proxy that is not characterised (Sections 2.2.4 and 2.2.9, Table S1). The reported shares of P6 and P8 should therefore be understood as including part of the cooling and storage burdens, not as attributable solely to kiln combustion or grinding energy. Other gaps documented in Table S1 include packaging materials, which were not modelled, electricity not entered for P4 and P5, silo dust not converted to a per-tonne value, and some kiln emissions extrapolated from periodic measurement campaigns. The modelled electricity total is 114.5 kWh/t cement, against the 110.25 kWh/t midpoint of the supplied range, because clinker-related stages use the model clinker ratio of 0.775. Natural gas consumption (410 t/year) was also excluded because the available information was insufficient to establish its use and reliably allocate its environmental burdens to the relevant production stages. Because natural gas and packaging are omitted, the climate change result may be lower than that of a complete A1–A3 inventory, and the impacts may be underestimated. Future refinement could disaggregate these flows, for example, by allocating cooler fan electricity and compressed air to P7 from installed equipment power and storage-related consumption to P9, provided plant-specific metering data become available. Such data were not available at the required resolution here.

(3) Representativeness of the modelled scenario. The assessment combines a market-representative recipe, averaged over three products, with foreground process data from a single plant (Section 2.2.1). This approach reflects the availability of sufficiently detailed plant-specific inventory data; comparable operational data for multiple facilities were not available to establish a consistent multi-plant inventory. Rather than introduce hypothetical values or combine inconsistent datasets, the assessment uses the available data to characterise the investigated production system transparently. It reflects one process inventory, fuel system, electricity supply, raw material composition and clinker-to-cement ratio (775 kg/t), as discussed in Section 4.3. Variations in clinker content, process efficiency, fuel composition, electricity carbon intensity and raw materials between plants, as well as the variability among the EPD sources in Table 8, can produce meaningfully different

profiles for cements with the same designation. The calculated 772.22 kg CO_2-eq/t cement is representative of the investigated scenario and not a universal value for CEM II/A-L 42.5 R.

(4) Background inventory and impact assessment method. Electricity- and fuel-related impacts depend on the background datasets. All electricity is represented by a single Serbian market dataset from ecoinvent v3.1 (2014), which is older than the plant data. ReCiPe Midpoint (H) v1.11 [28,34] determines how interventions are characterised into the eighteen calculated midpoint indicators, and ReCiPe 2016 and EF 3.1 were not applied. These dependencies are particularly consequential for human toxicity, ecotoxicity, ionising radiation and resource depletion, where upstream background processes contribute substantially. Water depletion was excluded from the interpretation because the Serbian electricity dataset, as characterised in ReCiPe Midpoint (H) v1.11, produced a physically implausible net value (Section 3.1). Water-related impacts should be reassessed with an AWARE-based water scarcity method and an updated electricity dataset. The absolute values, and potentially the ranking of stages within a category, may differ under other datasets, grid mixes or methods. Neither background-data nor LCIA-method uncertainty was quantified (Supplementary Table S5). The versions used reflect the software and database resources available for the present study. Although newer datasets and impact assessment methods could provide an updated perspective, their effects on the results were not evaluated.

(5) Uncertainty and sensitivity approach. The uncertainty and sensitivity analyses are limited by the available inventory data and modelling assumptions. The ±11% estimate covers the assigned data quality uncertainty of the process-stage contributions, while the ±30% sensitivity analysis is a deterministic, local assessment of stage contributions rather than a probabilistic analysis (Sections 3.5 and 3.6). Uncertainty in background datasets, the impact assessment method, structural model assumptions and category-specific hotspot rankings was not quantified. These limitations should be considered when interpreting the results.

(6) System-boundary scope. The study covers cement production up to the plant gate. Cement transport, concrete production and mix design, construction, use (including any long-term carbonation uptake), demolition and end-of-life treatment are outside the boundary, consistent with the A1–A3 cradle-to-gate scope of the EPDs compared in Table 8 [20,21]. The conclusions relate to cement manufacture up to the plant gate and not to the complete life cycle of construction products. This distinction matters when the results are used to inform decisions, such as concrete mix design, that require a cradle-to-grave perspective.

(7) Directions for future work. Future work should prioritise: (I) improving the resolution and representativeness of the inventory through measured raw-meal LOI and degree of calcination, stage-specific electricity metering, inclusion of natural gas and packaging, more detailed allocation of auxiliary flows (particularly for P7 and P9), and plant-specific electricity and fuel data; (II) a probabilistic (Monte Carlo) uncertainty analysis with correlated inputs, together with scenario and global sensitivity analyses, extending beyond the local approach of Section 3.6, to examine the joint influence of the clinker-to-cement ratio, alternative-fuel use, electricity-mix decarbonisation and process efficiency on the complete seventeen-category profile; (III) a flow-level contribution analysis to identify the inputs behind the P8 metal-depletion result (Section 4.4) and the flows in the background electricity dataset that produced the implausible water-depletion value (Section 3.1), a reassessment of water-related impacts with an AWARE-based water-scarcity method and an updated electricity dataset, along with a comparison with ReCiPe 2016 and EF 3.1; and (IV) extending the system boundary beyond the plant gate, including modules A4 to D of EN 15804 [20,21], so that the implications of different cement compositions can be evaluated at the level of concrete formulation or construction applications. Together, these refinements would reduce structural and parameter uncertainty and give a stronger

basis for improvement strategies that remain beneficial across the full multi-impact profile, and not only under the climate change focus that has historically dominated cement-sector decarbonisation reporting.

(8) Verification of constituent datasets. The linkage of the gypsum and slag datasets used in P8 was not verified at the flow level. Their contribution to metal depletion and, possibly, to climate change should be checked, and the statement that slag carries no upstream burden under the cut-off approach should be read as the intended modelling convention and not as a verified property of the dataset.

5. Conclusions

This study assessed the environmental impacts of a representative CEM II/A-L 42.5 R cement using a process-level life cycle assessment of ten foreground production stages (P1–P10), with a functional unit of 1000 kg of cement at the plant gate and ReCiPe Midpoint (H) v1.11 across eighteen impact categories.

The calculated climate change impact was 772.22 kg CO_2-eq per tonne of cement, within the range of two published EPD values for CEM II/A-L 42.5 R cement from a single producer (719.27 and 809.00 kg CO_2-eq/t). This comparison provides context rather than a product ranking. The rotary kiln (P6) contributed 67.7% of the climate change impact and the preheater and partial calcination stage (P5) contributed 15.5%, giving a combined contribution of approximately 83.2%. Because the allocation of emissions between these stages relies on modelling assumptions, the combined contribution is less dependent on the assumed P5/P6 split than on their individual contributions, although it remains dependent on the estimated total calcination emissions and the associated inventory assumptions. Calcination-related and fuel-combustion CO_2 together accounted for approximately 80% of the total climate change impact. The baseline contribution analysis therefore identifies pyro-processing as the principal climate change hotspot within the investigated system.

The dominant process stage varied across impact categories. P6 was the largest contributor in eight of the 17 interpreted categories, although its lead over P8 was narrow for human toxicity and particulate matter formation. Fuel storage, grinding and dosing (P4) was the largest contributor to ozone depletion, ionising radiation, fossil depletion, urban land occupation and natural land transformation. Cement grinding with additions (P8) dominated freshwater eutrophication, freshwater ecotoxicity, agricultural land occupation and metal depletion, accounting for approximately 97.8% of the metal-depletion result; the flows responsible for this result require further investigation before they are interpreted as a grinding-related hotspot. Water depletion also showed a negative net value, which arises from the background Serbian electricity market dataset and its characterisation in ReCiPe Midpoint (H) v1.11, rather than from a physical water saving; it was therefore reported but excluded from the interpretation (Section 3.1; Table S4). These findings indicate that climate change alone does not capture the full range of environmental hotspots. The clinker content of 775 kg/t is an important characteristic of the modelled composition, although it was not varied in a scenario analysis. Clinker-content reduction, improvements in preheater and kiln efficiency, fuel-mix decarbonisation and CO_2 capture are potential improvement pathways, subject to the performance requirements and environmental burdens of alternative materials.

The results should be interpreted in light of the study's system boundary, single-plant foreground inventory and data quality limitations. Calcination-related and fuel-combustion CO_2 emissions were estimated using assumptions, natural gas consumption and packaging were excluded, and P7 and P9 show zero impacts because of the model structure and available data, not because these stages have no environmental burdens. The estimated ±11% uncertainty represents the uncertainty quantified under the adopted data

quality assumptions and does not encompass all sources of uncertainty. The contribution-based sensitivity analysis indicates the relative influence of the assigned process-stage contributions but does not independently test the underlying inventory parameters or validate the emission estimates. Further analysis of raw-meal loss on ignition, the allocation of calcination emissions between P5 and P6, fuel properties and clinker content would be needed to examine these uncertainties more directly. Accordingly, the findings identify environmental hotspots and potential improvement priorities for the investigated production scenario but should not be generalised to all cement marketed under the CEM II/A-L 42.5 R designation.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su182111252/s1: Table S1: Life-cycle inventory of the studied cement (cradle-to-gate, functional unit 1000 kg CEM II/A-L 42.5 R); Table S2: Scaling factors applied to individual production stages for normalisation to the functional unit of 1 tonne of representative CEM II/A-L 42.5 R cement; Table S3: Reconciliation of scaled process contributions; Table S4: Relative contribution (%) of individual cement-production stages to the ReCiPe Midpoint (H) v1.11 impact categories for 1 tonne of modelled CEM II/A-L 42.5 R cement; Table S5: Uncertainty and sensitivity assumptions applied in the interpretation of the LCA results.

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Abbreviations

BREF	Best Available Techniques Reference Document
CEM	Cement type designation according to EN 197-1
CFC-11	Trichlorofluoromethane
1,4-DB	1,4-Dichlorobenzene
ED-XRF	Energy-dispersive X-ray fluorescence
EN	European Standard
EPD	Environmental Product Declaration
GWP100	Global warming potential over 100 years
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life-cycle assessment
LCI	Life-cycle inventory
LCIA	Life-cycle impact assessment
LOI	Loss on ignition
NMVOC	Non-methane volatile organic compounds

PM_{10}	Particulate matter with a diameter of 10 μm or less
SRF	Solid recovered fuel
TGA	Thermogravimetric analysis

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