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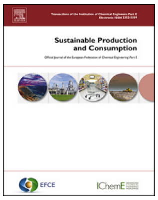

Research article

Environmental benchmarks for the European cement industry

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ABSTRACT

The urgent need to address climate change has pushed Europe to the forefront of environmental legislation initiatives, such as the Environment Action Program (EAP) within the European Green Deal and the disclosure of Environmental Product Declarations (EPDs) in the construction sector. The cement industry plays a vital role in this transition because it is one of the biggest contributors to greenhouse gas emissions worldwide. EPDs have managed to articulate the environmental information flow across different stakeholders, allowing them to incorporate sustainability design practices at the manufacturing, construction, and design levels. However, current EPDs are deterministically disclosed and lack benchmarks, hindering effective comparison and impeding sustainable material development. To address this challenge, the present research introduces a novel Life Cycle Assessment (LCA)-based probabilistic analysis to develop clinker and cement benchmarks. The proposed method incorporates data from industry reports, environmental databases, and EPDs, to generate the stochastic benchmarks. Moreover, a wide range of environmental performance indicators at a national level in Europe are covered, offering a holistic perspective beyond climate change. The results highlight the benefits of using country-specific environmental benchmarks, reducing the standard deviation of results by 2 to 7 times compared to background datasets. The reduction of clinker content proved to reduce 7 to 9 kg CO_{2eq}/t for every 1% reduction in all countries. However, it also increased other indicators depending on the mineral component used as a replacement, underscoring the need for holistic analysis. The research also exposes discrepancies between EPDs and industry-related data, accentuating the need for stochastic information disclosure to enhance reliability and facilitate decision-making by stakeholders. Another significant contribution of this research is the development of an extensive open-access database, providing a reference for future developments regarding sustainable cement and concrete.

1. Introduction

The consequences of climate change are visible today. The International Panel on Climate Change (IPCC) reported a surge in global adverse impacts on health and wellbeing on cities, settlements, and infrastructure linked to climate change in their latest report (IPCC, 2022). Moreover, the recent update on the planetary boundaries framework (Richardson et al., 2023), first introduced by Rockström et al. (2009), reveals that Earth is already surpassing high-risk zones concerning biosphere integrity, novel entities, biogeochemical cycles, land system change, and freshwater change, besides climate change. In this context, Europe is taking a lead role by introducing cutting-edge legislation to accelerate the transition toward a balanced relationship with the environment. Key initiatives include the Environment Action Programme (EAP), built on the European Green Deal, the Circular Economy Action Plan, the EU Industrial Policy, and the European Climate Law.

The cement industry plays a decisive role in this transition. On the one hand, it contributes nearly 7% of global anthropogenic greenhouse gas emissions (Sambataro et al., 2023a). On the other hand, cement stands as the world's second most used substance, after water, enabling cost-effective and energy-efficient infrastructure development (Scrivener et al., 2018). Despite these advancements, challenges persist in integrating environmental data into the early stages of building design. Environmental Product Declarations (EPDs) have emerged as pivotal tools, employing the Life Cycle Assessment (LCA) methodology (ISO, 2006) to quantify the environmental impacts throughout a product's life cycle. However, EPD information is typically presented as deterministic values, and, due to confidentiality concerns, the specific input data used for the calculations is not disclosed. Consequently, architects and designers face an arduous challenge when attempting to compare EPDs across different products, as there is a lack of reference scenarios and harmonization (Gelowitz and McArthur, 2017). This

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List of abbreviations

Abbreviation	Description
AP	Acidification Potential
CV	Coefficient of Variation
DQI	Data Quality Indicator
EAP	Environment Action Program
EDB	Environmental Data Base
EP	Eutrophication Potential
EPD	Environmental Product Declaration
ET	Ecotoxicity
GGBFS	Ground Granulated Blast Furnace Slag
GNR	Getting the Numbers Right
GWP	Global Warming Potential
HT-Cancer	Human Toxicity: Carcinogenic
HT-NonCancer	Human Toxicity: Non-Carcinogenic
IPCC	International Panel on Climate Change
IR	Industry Report
KEPI	Key Environmental Performance Indicator
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MIC	Mineral Component
MMD	Metals & Minerals Depletion
NR	Non Renewables
ODP	Ozone Depletion Potential
PDF	Probability Density Function
PM	Particulate Matter
POCP	Photochemical Oxidant Formation Potential
WD	Water Deprivation

challenge extends to product designers, who in turn struggle to define precise and accountable environmental targets, thereby hindering the transition towards more sustainable construction materials and practices. In addition, there is an absence of a standardised environmental design methodology that incorporates the inherent uncertainty in the environmental performance of different construction products.

Considering uncertainty in LCA is not new. Weidema et al. (1996) presented a framework for the inclusion of data quality indicators (DQIs) to account for the reliability of the information. This approach was further developed by Coulon et al. (1997) and Canter et al. (2002). The former called for improved transparency in LCA studies, while the latter presented a stochastic model to strengthen the LCA inventory phase, emphasising key processes in the final output. Uncertainties in LCA are divided into parameter, scenario, and model uncertainties, and all of them have a direct influence on the LCA results (Gregory et al., 2016; Huijbregts et al., 2003). Sugiyama et al. (2005) suggested using statistical inputs to reveal uncertainty-related information in industry-based Life Cycle Inventory (LCI), enhancing transparency while preserving data confidentiality. Recent developments, such as the probabilistic-based framework for EPD comparison suggested by Azari-Jafari et al. (2021), have aimed to provide a more comprehensive and robust comparison of different products by including the uncertainty of different sources. However, as the authors acknowledged, the selection of the LCI database plays a vital role in the comparison.

Examining the cement environmental footprint, Geng et al. (2019) demonstrated considerable variability in the clinker carbon footprint in China, ranging from 750 to 840 kg CO_2/t. This variability manifests as a variable embodied footprint at the building level later on (Zhang et al., 2019). Moreover, Zhu et al. (2015) showed that using standard CO_2 emission factors could overestimate China's national emissions by as much as 40% when compared to the ones derived from the stochastic analysis on carbon content, heating value, and oxidation value of hard coal fuel. This suggests that the use of stochastic analysis could yield much more accurate results. In the United States, DeRousseau et al. (2020) disclosed that the cement carbon footprint ranges between 640 and 1000 kg CO_2/t, with a higher frequency observed between 755 and 820 kg CO_2/t. However, details regarding the variability of additional environmental burdens were overlooked and remain limited in numerous LCA studies, stressing out the need for comprehensive assessments beyond the carbon footprint.

Interest is growing in fostering closer collaboration between construction materials manufacturers and building designers by incorporating Key Environmental Performance Indicators (KEPIs) in the form of EPDs. This aligns with Europe's strategic focus on developing sustainable construction materials. However, realising this goal demands two critical components, currently missing in the European context: i) establishing a reference benchmark to facilitate a comprehensive environmental performance comparison; and ii) implementing stochastic analysis for robust reliability studies.

This research aims to introduce an LCA-based probabilistic benchmark of the environmental impact of clinker and cement manufacturing in Europe. This novel methodology intends to overcome traditional deterministic LCA study limitations by covering the full spectrum of expected environmental impact frequencies and indicators. The multi-step approach integrates diverse data sources, including industry reports (IRs), environmental databases (EDBs) and EPDs to generate and validate the stochastic benchmarks. Different KEPIs are studied on a country level, extending beyond the current climate change focus and improving the granularity of data availability in the European context. A holistic environmental study of 300 existing EPDs is conducted, and an extensive database is generated and disclosed, serving as a reference for different stakeholders and future developments, including net-zero concrete materials.

2. Methodology

In this study, a stochastic LCA is conducted to analyse the manufacturing of clinker and cement in Europe at the country level. The framework developed for this research is illustrated in Fig. 1. Three different sources of information are used and statistically compared. First, IRs are analysed (Level 1). The most recent industry report from *Getting the Numbers Right* (GNR) (Global Cement and Concrete Association, 2022) is employed for clinker and cement, providing statistical insights into fuel and electricity consumption during their production in Europe. This information is complemented with background environmental data from Ecoinvent v3.9 to translate it into KEPIs. Then, Ecoinvent v3.9 is used as EDB (Level 2), where relevant activities and emissions are stochastically transformed into KEPIs. A preliminary comparison is made between Level 1 and Level 2 data. Finally, over 300 current EPDs (Level 3) are analysed, contributing to a conclusive comparison and validation.

2.1. LCA methodological approach

This study aims to statistically analyse the variability of KEPIs during clinker and cement manufacturing in Europe. To this end, the cradle-to-gate approach is employed, and one tonne (1 t) of material is considered the functional unit. The environmental impact associated with clinker production is controlled by three main processes: i) the fuel consumption in the kiln during combustion; ii) the electricity consumption in the plant for operation (crushing, milling, and sieving) and buildings; and iii) the decomposition of carbonates during calcination (Çankaya et al., 2015). The concept of cement equivalent is used. This means that the clinker-to-cement ratio is statistically simulated, representing country-specific distributions, and a representative national mix of supplementary cementitious materials is added accordingly. The Life Cycle Impact Assessment (LCIA) is performed using the EN15804 reference package 3.1 from the European Platform on LCA (European Commission) because it is the framework used for the generation of EPDs. The impact categories selected for the comparison were total Global Warming Potential (GWP), Human Toxicity Carcinogenics (HT-Cancer) and Non-Carcinogenics (HT-NonCancer), Ozone Depletion Potential (ODP), Particulate Matter (PM), Photochemical Ozone Creation Potential (POCP), Acidification Potential (AP), Ecotoxicity (ET), Eutrophication Potential (EP), abiotic depletion potential

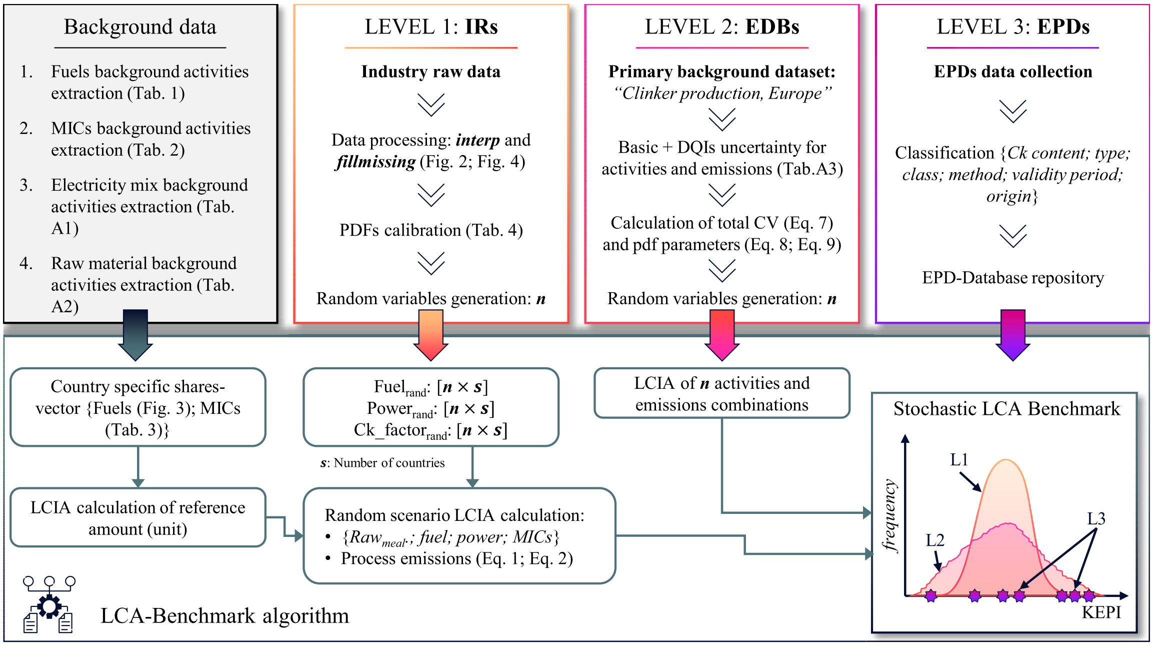


Fig. 1. Methodology framework for the generation of LCA-based environmental benchmarks.

of Non-Renewables (NR), Metals and Minerals Depletion (MMD), and Water Deprivation (WD).

2.2. LCI data sources

In this work, the data sources used for the LCI are categorised into three levels, as shown before, spanning from the industry to consumers. Firstly, up-to-date industry-related information (Global Cement and Concrete Association, 2022) is used for clinker and cement manufacturing. The data encompasses 75% of total cement manufacturing in Europe from 2005 to 2020, with coverage exceeding 95% of total cement production in some countries, such as Germany, France, Poland, and the UK. Aggregated figures in the form of statistical distributions are utilised for non-linear regression of Probability Density Functions (PDFs), representing the stochastic nature of these processes. Secondly, the clinker manufacturing activity dataset from Ecoinvent v3.9 (Kellenberger et al., 2007) is used, as this is normally considered for generating EPDs. An uncertainty analysis is performed for all upstream activities and emissions within the main product. Thirdly, a thorough analysis is conducted on over 300 open-access EPDs, covering cement products in Europe. These are classified based on the reported clinker-to-cement ratio, type and class of cement, country of origin, validity period, and the methodology applied during calculation. A comprehensive database is presented in the supplementary file and is available in an online repository.

2.3. Stochastic analyses

2.3.1. Clinker and cement production: industry reports

Clinker The production of clinker consists of calcining around 1.52 t of raw materials per tonne of clinker, usually a mix of limestone and clay, at about 1450 °C of temperature (Chen et al., 2010; Moya et al., 2010). The environmental burdens of this process are highly influenced by the kiln technology and fuels used during combustion. The use of pre-heaters increases the efficiency of the calcination, requiring between 3000 and 4200 MJ/t of energy for a dry process, although some studies suggest even lesser amounts (Rahman et al., 2013). In contrast, semi-dry/semi-wet process consumption, also known as Lepol kilns, can range between 3300 and 5400 MJ/t, while wet processes can reach up to 6400 MJ/t clinker (Schorcht et al., 2013). Over the last decades, Europe has pursued a transformation towards the use of more efficient kilns and consistently increased the use of alternative fuels, as shown in Fig. 2. Today, over 80% of the clinker is produced in dry kilns with preheaters, while less than 50% of direct fossil fuels are consumed (Global Cement and Concrete Association, 2022).

A methodology to analyse the variability of energy and electricity in clinker production is developed. First, the variability in terms of fuel and electricity consumption per tonne of clinker is analysed for each country from the reported data, as shown in Fig. 3. Both the upper and lower tales of the distributions are truncated to the extreme values (dashed lines) to fill up the missing data from the reported series, thus covering 100% of clinker production. To evaluate the influence of this approach on the overall outcome, a sensitivity analysis is performed by contrasting the results with two alternative methods. Both linear and cubic interpolation are utilised between the datasets' amounts and the minimal and maximal expected engineering values, derived from the limits of the 95% confidence interval of the global distribution. The analysis is detailed in the Annex section. Then, interpolation from the data is conducted, and PDFs are fitted using the MATLAB *fitdist* function. Log-normal distributions are adopted because they fit best into the actual data and avoid unrealistic negative values that may be encountered when using normal distributions. The actual fitting against the raw data can be seen in the Appendix section. After that, a sample of 10000 points is randomly generated using the previously fitted PDFs for each country with the distribution parameters declared in Table 4. Once the vectors containing randomly generated amounts of fuel and electricity are created, the environmental impact of each scenario is calculated using a MATLAB-based algorithm developed by the authors (Sambataro et al., 2023b). To this end, the unitary KEPI of 1 MJ and 1 kWh for energy and electricity, respectively, in each country is calculated and then scaled to the randomly generated inventory amount.

As stated in GNR (Global Cement and Concrete Association, 2022; Klee et al., 2011), there are three main types of fuel: fossil, alternative fossils, and biomass. While fossil fuels are commonly known and used in LCA studies, datasets regarding alternative fossil fuels and biomass are scarce. The former includes the use of industrial wastes such as plastics, solvents, and tyres, while the latter predominately consists of animal bone meal, sewage sludge, and wood-based waste. In total, 22 different background activities were selected from Ecoinvent v3.9 for

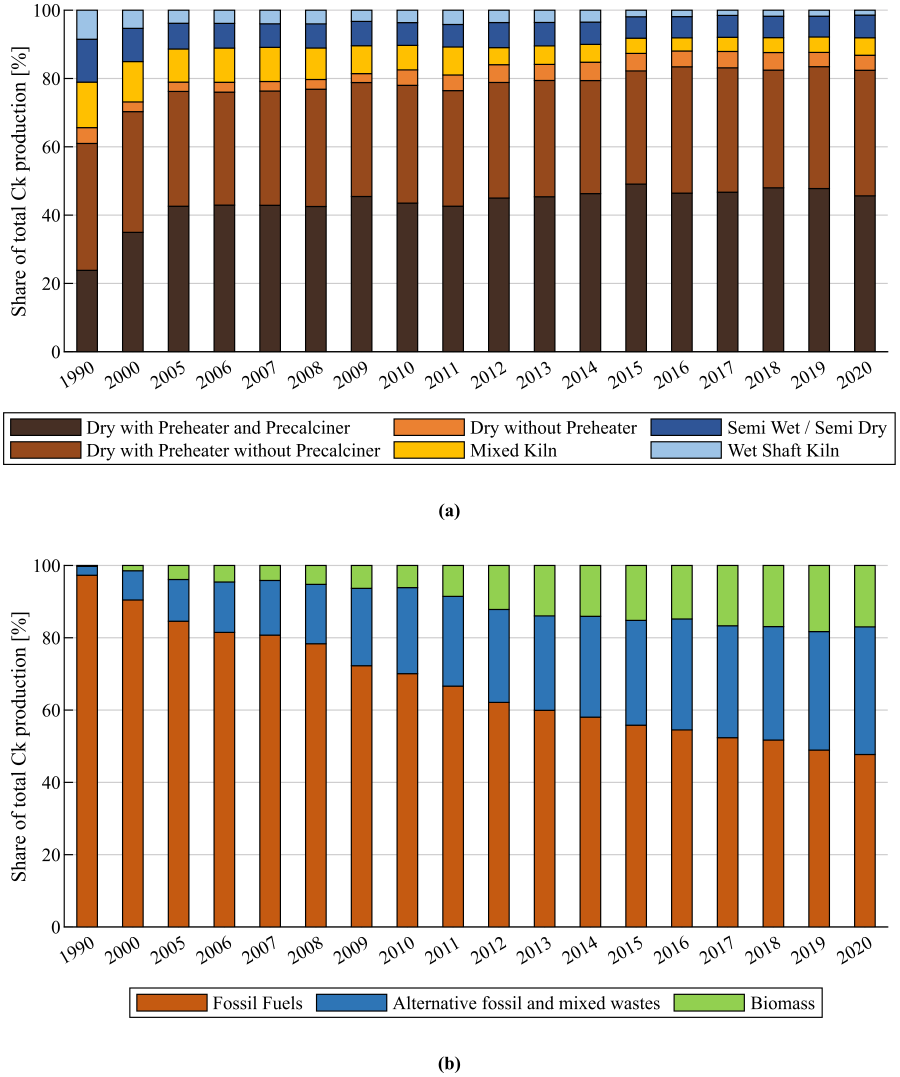
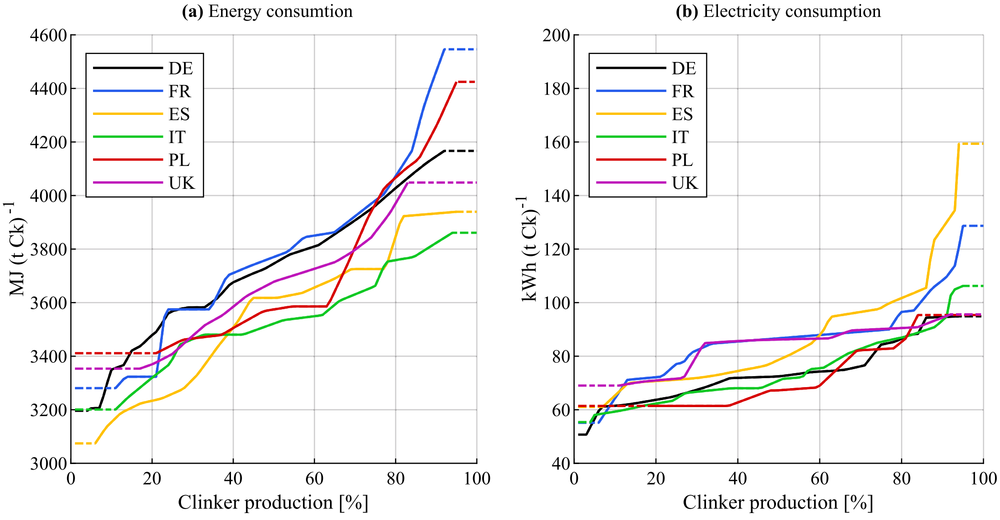


Fig. 2. Clinker manufacturing in Europe between 1990 and 2020: (a) per type of kiln; (b) per type of fuel.


(a) Energy consumtion

(b) Electricity consumption

Fig. 3. Statistical distribution of energy and electricity consumption during clinker manufacturing per country: (a) energy intensity; (b) electricity intensity. Dashed lines indicate truncated values.

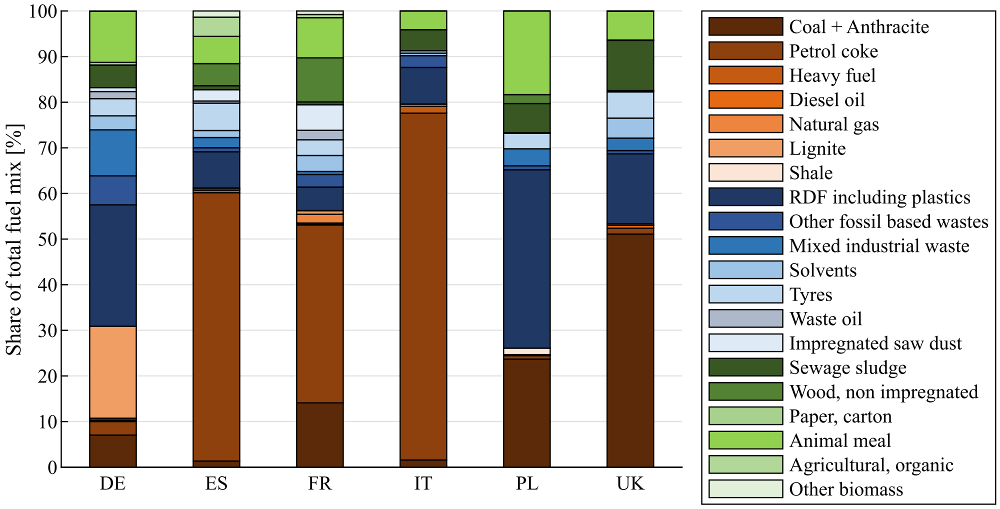


Fig. 4. Shares fuel types consumed per country.

the generation of representative fuel mixes. The total share of each fuel considered in the analysis is shown in Fig. 4 and Table 1, also available in the supplementary material file. For the case of alternative fuels, previous studies are considered for the calculation of the average net calorific value needed for the conversion to the mass unit of the reference product (Georgiopoulou and Lyberatos, 2018; Kääntee et al., 2004). Regarding the generation of electricity, national mixes are used for each country based on market activities, which are detailed in the supplementary file.

Finally, air emissions related to the calcination of raw materials (i.e., those not included in the fuel combustion) are considered in the analysis by using stoichiometric balances. The CO_2 emissions from the carbonate decomposition are simulated following the theoretical procedure proposed by Nie et al. (2022), where the associated emissions are calculated as:

$$m_{CO_2} = m_{CaCO_3} \times \frac{44}{100} + m_{MgCO_3} \times \frac{44}{84.3}, \tag{1}$$

where m_{CaCO_3} and m_{MgCO_3} are the mass contents of calcium carbonate and magnesium carbonate, respectively, per unit of clinker mass. The coefficients $\frac{44}{100}$ and $\frac{44}{84.3}$ are the relative molecular masses of CO_2 to $CaCO_3$ and $MgCO_3$, respectively. It was assumed an average composition for the clinker of 65% C3S, 15% C2S, 10% C3A, and C4AF (Schorcht et al., 2013), which results in the addition of 537,5 kg CO_2 per tonne of clinker. Moreover, sulphur emissions to the air are added using Eq. (2), by considering the volumetric flow rate of the flue gas as formulated in Kookos et al. (2011):

$$m_{SO_3} = 22414 \times C_{SO_3} \times \sum_{g \in FG} \frac{m_g}{mw_g} \tag{2}$$

where m_{SO_3} is expressed in kg SO_3 per tonne of clinker, C_{SO_3} is the concentration of SO_3 in the flue gas, taken as 300 mg/Nm^3 (Berdowski et al., 2019; European Commission, 2013), m_g and mw_g are the mass and molecular weight of the g gaseous component in the flue gas (FG) and 22,414 expressed in l/mol. The flue gas composition is based on the mass balance of CO_2, O_2, and N_2, which depends on the raw material fuel mix used and kiln technology. An average value of 2300 m^3/t is used for the calculations (Berdowski et al., 2019). Nitrogen oxides are not considered separately because their emission is related to fuel combustion and therefore considered in the corresponding activities (Schorcht et al., 2013).

Cement The cement environmental benchmark is built upon the cement equivalent concept. For this, information regarding the statistical distribution of the clinker-to-cement ratio in the different countries is used; see Fig. 5a. The data is treated similarly to the fuel requirement in the clinker plant. The power consumption per unit of cement equivalent was used instead of the one calculated for clinker manufacturing, based on the statistical distribution shown in Fig. 5b. It should be highlighted, that the fly ash used as a supplementary Mineral Component (MIC) is commonly not milled since it has a relatively small particle size distribution and is therefore mixed directly in the cement. Thus, this is considered implicitly in the calculation of the electricity consumption per unit of cement equivalent, because of the stochastic approach.

After generating the random variables, which comprise the clinker content in the cement equivalent binder mix, the country-specific MICs mix obtained from GNR (Global Cement and Concrete Association, 2022) is added. Background data sets are selected from Ecoinvent and are displayed in Table 2. These activities correspond directly to the declared functional unit, so no allocation is needed. For the case of fly ash, the hard coal electricity production activity is used as a proxy, since this is the main activity from which fly ash is generated as a by-product. It is assumed that, on average, 0.052 kg of fly ash is generated for every kWh produced (Van Den Heede and De Belie, 2012). Then, economic allocation factors are derived for each country (Chen et al., 2010) based on actual local price data (Trading Economics, 2023). The total shares and allocation factors used are displayed in Table 3.

2.3.2. Temporal evolution

Following the European goals, it is expected that most of the KEPIs will be considerably reduced over the years. Therefore, the temporal evolution of the selected KEPIs is analysed in the case of Germany. Input parameters for the years 2008, 2012, 2016, and 2020 are selected, and the previously described methodology is applied. To analyse the evolution of the KEPIs quantitatively and qualitatively, the results are compared in terms of relative performance against the reference year of 2008, as follows:

$$Ck_{KEPI_{i,j,norm}} = \frac{Ck_{KEPI_{i,j}}}{Ck_{KEPI_{i,2008}}}, \tag{3}$$

and

$$CEM_{KEPI_{i,j,norm}} = \frac{CEM_{KEPI_{i,j}}}{CEM_{KEPI_{i,2008}}}, \tag{4}$$

where $Ck_{KEPI_{i,j,norm}}$ and $CEM_{KEPI_{i,j,norm}}$ are the normalised ith KEPI corresponding to the jth year of the clinker and cement equivalent manufacturing, accordingly, and $Ck_{KEPI_{i,j}}$ and $CEM_{KEPI_{i,j}}$ are the absolute values.

Table 1
Background fuel consumption activities.

Name	Type	CV [MJ/kg]	Activity Name	Geography	Reference Product Name	Unit	Reference Amount
Coal + Anthracite	Fossil		heat production, at hard coal industrial furnace 1-10MW	Europe without Switzerland	heat, district or industrial, other than natural gas	MJ	1
Petrol Coke	Fossil		heat production, heavy fuel oil, at industrial furnace 1MW [a]	Europe without Switzerland	heat, district or industrial, other than natural gas	MJ	1
(Ultra) Heavy Fuel	Fossil		heat production, heavy fuel oil, at industrial furnace 1MW	Europe without Switzerland	heat, district or industrial, other than natural gas	MJ	1
Diesel Oil	Fossil		heat production, light fuel oil, at industrial furnace 1MW	Europe without Switzerland	heat, district or industrial, other than natural gas	MJ	1
Natural Gas	Fossil		heat production, natural gas, at industrial furnace >100kW	Europe without Switzerland	heat, district or industrial, natural gas	MJ	1
Lignite	Fossil		heat and power co-generation, lignite	DE	heat, district or industrial, other than natural gas	MJ	1
Shale	Fossil		heat production, light fuel oil, at industrial furnace 1MW	Europe without Switzerland	heat, district or industrial, other than natural gas	MJ	1
Rdf Including Plastics	AF	32.4	treatment of waste plastic, mixture, municipal incineration	RoW	waste plastic, mixture	kg	-1
Other Fossil Based Wastes And Mixed Fuels	AF	38.3	treatment of waste mineral oil, hazardous waste incineration	Europe without Switzerland	waste mineral oil	kg	-1
Mixed Industrial Waste	AF	38.3	treatment of waste mineral oil, hazardous waste incineration	Europe without Switzerland	waste mineral oil	kg	-1
Solvents	AF	22.7	treatment of spent solvent mixture, hazardous waste incineration	Europe without Switzerland	spent solvent mixture	kg	-1
Tyres	AF	28.4	treatment of used tyre	GLO	used tyre	kg	-1
Waste Oil	AF	38.3	treatment of waste mineral oil, hazardous waste incineration	Europe without Switzerland	waste mineral oil	kg	-1
Impregnated Saw Dust	AF		heat production, wood chips from industry, at furnace 1000kW	RoW	heat, district or industrial, other than natural gas	MJ	1
Sewage Sludge	Biomass	4.1	treatment of raw sewage sludge, municipal incineration	RoW	raw sewage sludge	kg	-1
Wood, Non Impregnated Saw Dust	Biomass	15.5	heat production, untreated waste wood, at furnace 1000-5000 kW	RoW	waste wood, untreated	kg	-1
Paper, Carton	Biomass	13.0	heat production, untreated waste wood, at furnace 1000-5000 kW	RoW	waste wood, untreated	kg	-1
Animal Meal	Biomass		heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas	RoW	heat, district or industrial, other than natural gas	MJ	1
Animal Bone Meal	Biomass		heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas	RoW	heat, district or industrial, other than natural gas	MJ	1
Animal Fat	Biomass		heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas	RoW	heat, district or industrial, other than natural gas	MJ	1
Agricultural, Organic, Diaper Waste, Charcoal	Biomass		heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas	RoW	heat, district or industrial, other than natural gas	MJ	1
Other Biomass	Biomass	15.5	heat production, untreated waste wood, at furnace 1000-5000 kW	RoW	waste wood, untreated	kg	-1

[a] Used as a proxy, heavy fuel oil is replaced by petroleum coke using a CV of 35 MJ/kg.

Table 2
Background MICs activities.

Name	Activity Name	Geography	Reference Product Name	Unit	Reference Amount
Gypsum	market for gypsum, mineral	RER	gypsum, mineral	kg	1
Limestone	market for limestone, crushed, for mill	RoW	limestone, crushed, for mill	kg	1
Pozzlana	market for limestone, crushed, for mill	RoW	limestone, crushed, for mill	kg	1
Slag	market for ground granulated blast furnace slag	RoW	ground granulated blast furnace slag	kg	1
Fly Ash	electricity production, hard coal	RoW	electricity, high voltage	kWh	1

Table 3
Country-specific MICs distribution.

Country	Gypsum	Limestone	Pozzlana	Slag	Fly Ash	Price [euros/kWh]	Allocation FA
DE	20.5%	21.6%	0.5%	56.3%	1.1%	0.106	0.98%
FR	18.6%	35.5%	1.2%	43.1%	1.5%	0.134	0.78%
ES	23.6%	46.1%	10.2%	7.0%	13.2%	0.110	0.95%
IT	19.3%	62.0%	6.5%	5.7%	6.5%	0.123	0.85%
PL	20.7%	14.4%	0.2%	37.1%	27.7%	0.124	0.84%
UK	42.8%	49.8%	0.0%	0.5%	6.9%	0.092	1.13%

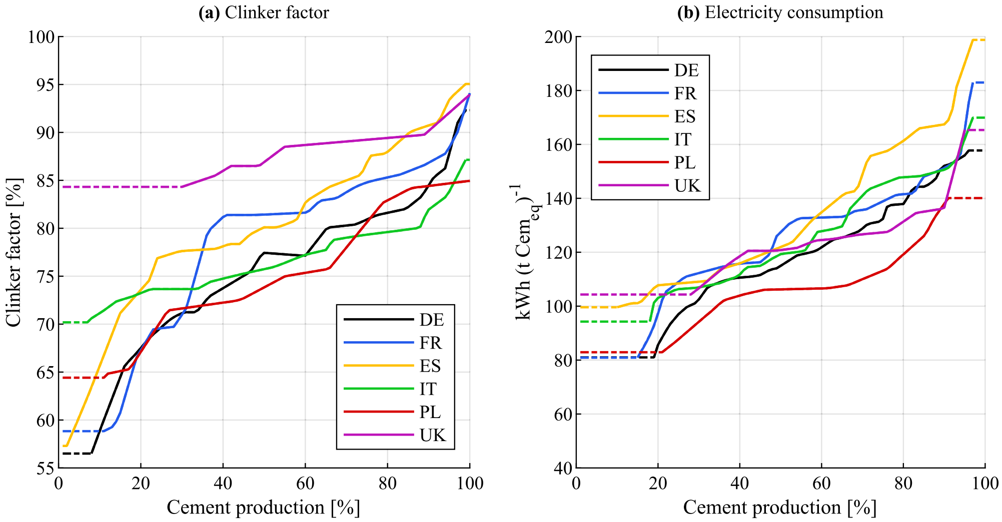

(a) Clinker factor **(b)** Electricity consumption

Fig. 5. Statistical distribution for cement equivalent manufacturing. (a) clinker factor; (b) electricity intensity. Dashed lines indicate truncated values.

Figs. 6a and 6b show the statistical evolution of both energy and electricity consumption during clinker manufacturing over the years. Additionally, Figs. 6c and 6d illustrate the parameters for the cement equivalent evolution in Germany. Specific information regarding the fuel mixes and MIC shares can be found in the supplementary material.

2.3.3. Ecoinvent

The uncertainty of the Ecoinvent dataset *Clinker production* is considered for comparison with industry-related information. As stated in the Ecoinvent documentation (Kellenberger et al., 2007), the uncertainty is classified into basic and additional. The former is related to the intrinsic variability and stochastic error of the parameters and depends on the type of intermediate activity or elementary exchange and the type of process considered. The latter represents the deficiency of the used data and is quantified through the use of DQIs in the form of a pedigree matrix.

The original dataset is used as a proxy and modified to generate a fair comparison. Infrastructure-related activities, such as the cement plant, refractory materials, and machines, were omitted. For each activity and emission, basic and additional uncertainty are accounted for. Using Eq. (5), the information in the form of the variance of the underlying log-normal distribution is transformed into the coefficient of variation (CV). This allows the use of any PDF later on (Muller et al., 2016) because it is a dimensionless measure of dispersion independent of the PDF considered. Assuming that the DQIs used in the pedigree matrix are independent of each other, the total additional uncertainty is calculated based on each CV, as shown in Eq. (6). Then, the total uncertainty CV_t is obtained from Eq. (7).

$$CV = \sqrt{exp(\sigma^2) - 1} \tag{5}$$

$$CV_a = \sqrt{\prod_{i=1}^{5} exp(CV_i^2 + 1) - 1} \tag{6}$$

$$CV_t = \sqrt{CV_b^2 + CV_a^2} \tag{7}$$

where CV_t, CV_b, and CV_a are the total, basic, and additional uncertainty, respectively. The coefficients of basic uncertainty (CV_b) depend on the type of activity or emission and are obtained from Weidema et al. (2013), while the additional component was derived from the pedigree matrix declared in the activity. As discussed by Zhang and Wang (2017), the use of normal distributions can lead to unreasonable negative values, and log-normal distributions may cause bias because of the long tail. The latter was observed in the present study, and therefore a triangular distribution is adopted. The function parameters are obtained as follows:

$$a = 2 \times b - c \tag{8}$$

$$c = (1 + \sqrt{6} \times CV_t) \times b \tag{9}$$

where a, b, and c are the lower limit, peak location, and upper limit. Each activity and emission and their uncertainty information are available in the supplementary file, together with the DQI parameters used.

3. Results

This section describes and analyses the obtained simulation results. Firstly, the calibrated parameters for the PDFs of each country are showcased. Secondly, the benchmark derived from clinker and cement manufacturing is unveiled in the form of country-specific histograms, along with the main distribution parameters. Thirdly, a comparative analysis between the statistically generated scenarios and the EPD databank is conducted. Lastly, the temporal evolution of selected KEPIs in Germany is explored.

3.1. Clinker and cement PDFs for each country

Table 4 outlines the selected PDFs and their key parameters for each of the input domains used in this study. The Annex section provides fur-

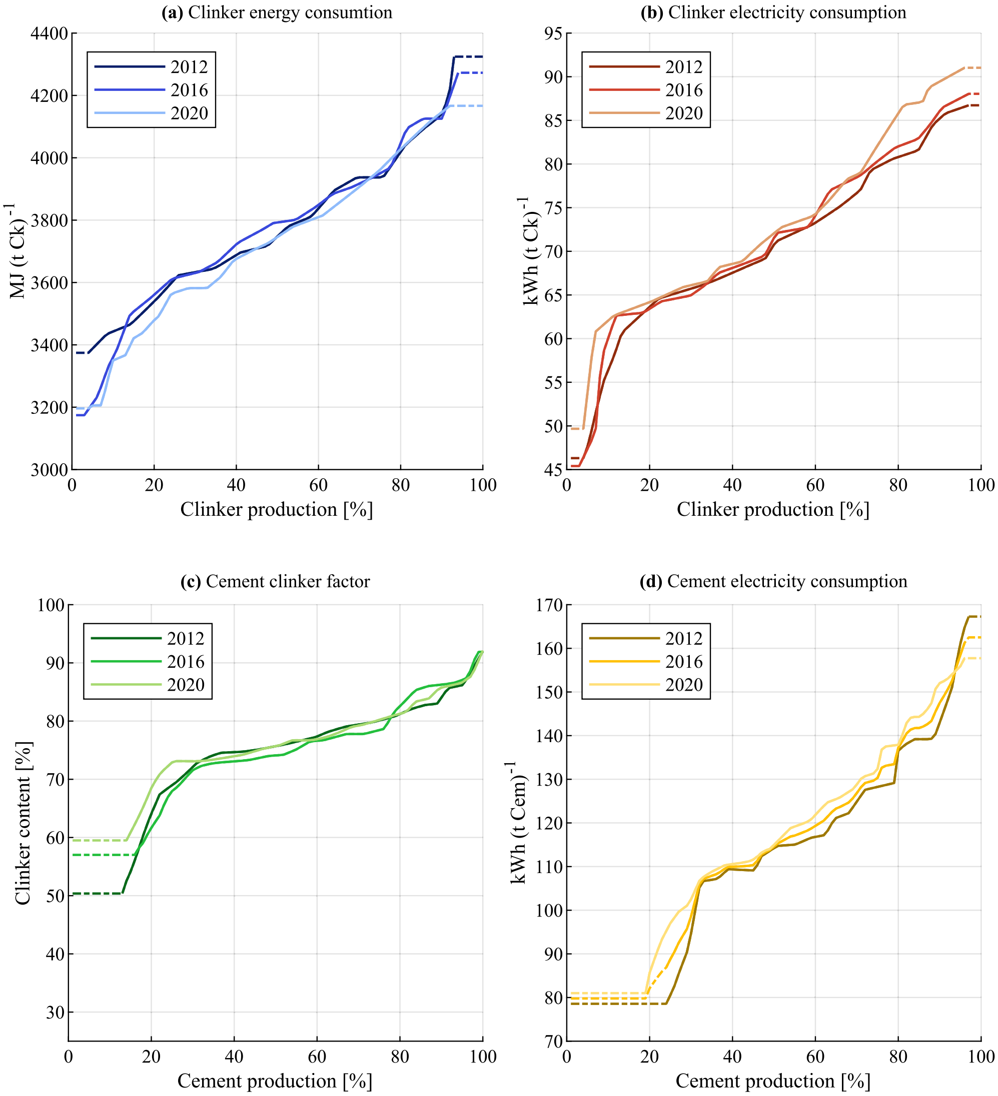


Fig. 6. Statistical evolution for clinker and cement manufacturing in Germany. (a) clinker energy intensity; (b) clinker electricity intensity; (c) cement clinker factor; (d) cement electricity intensity.

Table 4
PDF parameters obtained for clinker and cement in each country.

Input	Parameter	DE	FR	ES	IT	PL	UK
Energy intensity - clinker	Distribution	lognormal	lognormal	lognormal	lognormal	lognormal	lognormal
[MJ/t ck]	μ	8.224	8.238	8.172	8.168	8.214	8.207
	σ	0.077	0.099	0.080	0.058	0.086	0.068
Power intensity - clinker	Distribution	lognormal	lognormal	lognormal	lognormal	lognormal	lognormal
[kWh/t ck]	μ	4.299	4.445	4.455	4.303	4.273	4.420
	σ	0.159	0.197	0.257	0.180	0.171	0.112
Clinker factor - cement	Distribution	lognormal	lognormal	lognormal	lognormal	lognormal	lognormal
[% ck]	μ	4.307	4.340	4.375	4.336	4.308	4.469
	σ	0.126	0.138	0.120	0.053	0.091	0.030
Power intensity - cement	Distribution	lognormal	lognormal	lognormal	lognormal	lognormal	lognormal
[kWh/t cem]	μ	4.732	4.788	4.864	4.799	4.647	4.794
	σ	0.216	0.224	0.209	0.181	0.168	0.129

ther details on the calibration of simulated PDFs compared to the actual data. In addition, the sensitivity analysis results on the fill-up methodology used for data gaps are detailed. The results show that adopting extreme limits during the data gaps interpolation yields variations in the PDFs μ parameter under 0.2%, 0.7%, 0.9%, and 0.5% for the energy intensity, power intensities in clinker and cement, and the clinker ratio, respectively, across all countries except the UK. The latter exhibits a 2.2% absolute relative difference regarding the clinker factor μ parameter when adopting linear interpolation, dropping to 1.2% when cubic is used. The σ parameter exhibits much higher relative variation for all PDFs when compared to the original value, ranging from 11% to over 400%. However, when comparing the absolute difference against the original μ parameter, differences remain between 0.3% and 2.9%. Looking into the influence at the KEPI level, it is shown that the mean value across all KEPIs in all the countries analysed remains under 0.2% variation. The effect on the standard deviation is analysed by comparing the 95% confidence interval minimal and maximal values on all KEPIs across each country compared to the original one. It is shown that almost all the indicators exhibit differences under 3% in their limit values, highlighting the robustness of the current study. Only selected KEPIs in PL and UK, namely NRE and EP, show up to 13% difference.

On average, the energy intensity during clinker production varies from 3531 to 3799 MJ per tonne of clinker. Italy shows the lowest average value and variance, while France exhibits the highest average and variance. The power intensity for clinker manufacturing ranges from 72.8 to 89.0 kWh/t, with Poland having the lowest and Spain having the highest values. Similar to fuel, higher variance corresponds to higher average values, and vice versa. Electricity consumption in cement manufacturing follows a comparable pattern. It can be appreciated that it is, on average, 1.50 times higher than that associated with clinker. This is because of the additional grinding and milling of the clinker and other MICs. Poland shows the lowest average consumption at 105 kWh per tonne of cement equivalent. This is attributed to its higher use of fly ash, namely 27.7% of the total MIC distribution, as explained earlier. In contrast, Spain registers a 25% higher electricity demand, totaling 132.4 kWh/t. Variances follow the previously observed pattern. Regarding the clinker factor, the UK averages 87.3% content in their cement equivalent mix, nearly 10% more than the following Spain (ES) and 17% more than Poland, which has the lowest amount at 74.6%.

3.2. LCA probabilistic results

Table 5 presents the mean and standard deviation of the different KEPIs for both clinker and cement equivalent production across different countries, including the clinker manufacturing activity from the Ecoinvent dataset. Examining the results reveals that, except for ET, EP, and MMD, clinker generally performs poorly, indicating its higher environmental impact per tonne of material. The performance of ET and EP depends on the specific country under analysis, while for MMD, this is not the case. The MMD impact of cement equivalent is, on average, 7 to 8 times higher than that of clinker. This substantial difference is attributed to the relative impact on mineral additions, a point that will be elaborated on later. Furthermore, the standard deviation, representing variability, is consistently higher for cement than for clinker at the country level. Notably, the Ecoinvent dataset exhibits maximal variability in six out of twelve KEPIs, with the rest distributed among FR, DE, and ES, which aligns with expected results. France and Spain demonstrate high standard deviations in terms of clinker energy intensity, cement power intensity, and clinker factor, as previously explained. Germany exhibits notable variability in cement electricity intensity, particularly influencing the ET indicator. A detailed analysis of these findings is conducted in the subsequent subsections for each material.

3.2.1. Clinker Environmental Performance

Fig. 7 illustrates the benchmark through histograms focusing on clinker KEPIs, while Fig. 8 showcases the average relative contribution of fuel, electricity, process, raw materials, and MICs to each environmental indicator for both clinker and cement. Process-related emissions emerge as the most relevant for GWP, while playing a less significant role in terms of PM, AP, and ET and being irrelevant in the rest of the indicators. Fuel-related emissions predominantly control most KEPIs, except GWP, MMD, and, in some cases, WD. Electricity-related emissions play a significant role in non-renewable resource depletion, with their impact on other categories varying by the country analyzed. Notably, in Poland, they produce a substantial impact on many KEPIs due to the country's reliance on hard coal for electricity generation.

Fig. 7 reveals good agreement between histograms generated from industry-reported inventories and those derived from the Ecoinvent database. The latter exhibits higher standard deviations in most KEPIs compared to individual countries, with consistently more variability

Table 5
KEPIs obtained for clinker and cement equivalent in Europe, 2020.

Impact Category	Unit		Clinker							Cement equivalent					
			DE	FR	ES	IT	PL	UK	Ecoinvent	DE	FR	ES	IT	PL	UK
GWP	kg CO2 eq	μ	851.5	862.7	870.2	921.3	896.8	941.4	923.4	684.6	685.2	718.2	736.6	741.4	838.6
		σ	20.0	29.4	23.5	19.9	25.6	24.2	86.9	70.6	84.6	77.4	39.0	54.9	32.0
HT-Cancer	CTUh	μ	7.92E-08	1.17E-07	1.16E-07	1.28E-07	9.75E-08	1.02E-07	1.27E-07	7.31E-08	9.79E-08	1.00E-07	1.06E-07	9.74E-08	9.29E-08
		σ	3.78E-09	9.01E-09	7.04E-09	5.81E-09	5.96E-09	4.93E-09	2.66E-08	5.28E-09	1.17E-08	1.08E-08	6.69E-09	7.40E-09	5.01E-09
HT-NonCancer	CTUh	μ	2.04E-06	2.34E-06	1.95E-06	2.15E-06	3.37E-06	3.59E-06	6.23E-06	1.94E-06	2.00E-06	1.74E-06	1.81E-06	3.53E-06	3.23E-06
		σ	1.14E-07	1.90E-07	1.20E-07	9.81E-08	2.49E-07	2.10E-07	2.25E-06	1.46E-07	2.25E-07	1.68E-07	1.11E-07	3.07E-07	2.04E-07
ODP	kg CFC-11 eq	μ	1.59E-06	3.28E-06	3.93E-06	4.92E-06	1.31E-06	2.68E-06	2.84E-06	1.71E-06	2.89E-06	3.52E-06	4.37E-06	1.39E-06	3.06E-06
		σ	8.08E-08	2.68E-07	2.75E-07	2.54E-07	7.14E-08	1.56E-07	4.18E-07	1.13E-07	3.12E-07	3.86E-07	3.07E-07	8.08E-08	2.42E-07
PM	Disease incidence	μ	1.64E-05	3.05E-05	2.56E-05	2.79E-05	2.19E-05	3.50E-05	1.05E-05	1.40E-05	2.49E-05	2.11E-05	2.22E-05	1.80E-05	3.09E-05
		σ	6.17E-07	2.22E-06	1.37E-06	1.14E-06	1.12E-06	1.81E-06	6.23E-07	1.06E-06	3.14E-06	2.41E-06	1.37E-06	1.41E-06	1.81E-06
POCP	kg NMVOC eq	μ	0.63	1.17	1.13	1.25	0.93	1.21	1.70	0.60	0.98	1.00	1.07	0.92	1.11
		σ	2.75E-02	9.23E-02	6.86E-02	5.66E-02	5.41E-02	6.29E-02	1.29E-01	3.46E-02	1.16E-01	9.68E-02	6.44E-02	5.91E-02	6.18E-02
AP	mol H+ eq	μ	1.57	2.80	2.73	3.12	2.51	3.20	1.76	1.37	2.28	2.34	2.53	2.44	2.85
		σ	4.65E-02	1.88E-01	1.41E-01	1.25E-01	1.29E-01	1.52E-01	1.09E-01	9.74E-02	2.82E-01	2.35E-01	1.51E-01	1.60E-01	1.54E-01
ET	CTUe	μ	1020.2	1543.9	1765.0	2060.7	1040.5	1100.6	983.5	1610.2	1734.7	1540.6	1705.2	1448.4	992.0
		σ	47.3	119.7	111.2	98.9	55.3	50.1	115.4	200.8	123.8	145.3	101.6	103.3	50.8
EP	kg P eq	μ	2.30E-01	6.31E-02	2.92E-02	3.98E-02	1.82E-01	1.84E-01	6.70E-02	2.18E-01	5.27E-02	2.92E-02	3.61E-02	2.02E-01	1.63E-01
		σ	1.51E-02	4.90E-03	1.49E-03	1.52E-03	1.61E-02	1.15E-02	8.21E-03	2.47E-02	6.23E-03	1.88E-03	2.03E-03	2.13E-02	1.11E-02
NRE	MJ	μ	2005.6	4017.0	3697.5	4256.7	2426.2	3475.6	2860.0	2205.3	3934.2	3483.8	3742.5	2654.7	3443.8
		σ	116.7	328.9	272.7	214.9	171.3	179.1	299.2	199.0	439.7	358.9	252.4	209.5	199.7
MMD	kg Sb eq	μ	2.82E-04	3.02E-04	2.94E-04	2.93E-04	2.65E-04	3.01E-04	2.32E-04	2.18E-03	1.82E-03	1.98E-03	1.88E-03	2.17E-03	2.24E-03
		σ	6.32E-06	9.48E-06	9.28E-06	6.15E-06	5.55E-06	6.09E-06	2.53E-05	6.86E-04	6.80E-04	7.69E-04	2.70E-04	5.04E-04	3.99E-04
WD	m3 world eq	μ	97.90	64.32	58.66	67.04	72.71	68.95	46.45	82.84	60.38	54.66	66.47	68.36	63.64
		σ	4.00	2.60	2.62	2.95	2.95	1.67	8.06	7.71	5.49	5.05	5.12	4.75	2.31

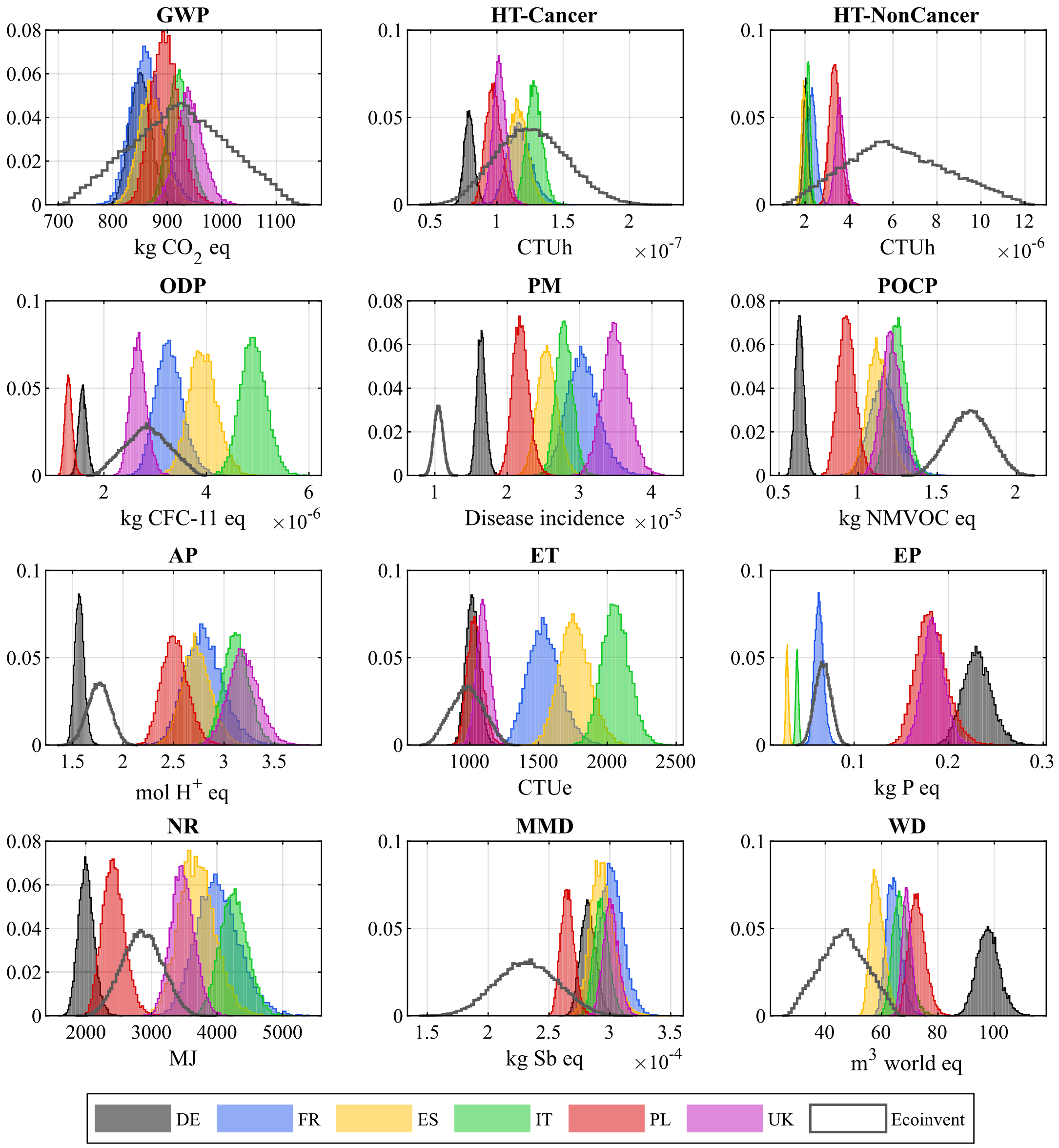


Fig. 7. Histograms of clinker KEPIs in Europe, 2020.

than the lowest standard deviation. The PM, AP, and EP indicators show less variation in the Ecoinvent activity. However, the clinker carbon footprint standard deviation is notably 3 to 4 times higher than those for each country, representing almost 10% of its mean value (86.9 kg CO_{2eq}/t vs. 923 CO_{2eq}/t). This KEPI aligns with Ecoinvent industry data, but discrepancies exist in other categories, as discussed in the EPD analysis. Specifically, the PM indicator shows a lower impact in Ecoinvent due to its inclusion of actual measured data, potentially leading to an overestimation in our study.

Fig. 7 also highlights a connection between the worst-performing countries in terms of human health-related impacts and the use of fossil fuels. This is particularly evident in carcinogenic substance emissions, where all fossil fuels generate a similar unitary impact (1.14 to 1.30 CTUh per MJ, except for lignite, whose impact is around 0.6 CTUh per MJ). Germany's lower reliance on fossil fuels explains its 20–40% lower cancerogenic footprint compared to other countries.

Italy, Spain, France, and the United Kingdom primarily source more than half of their fuel mix from fossil sources (Fig. 4). Nevertheless, it can be appreciated that the UK differentiates from the former three countries in carcinogenic emissions and ODP, particularly due to the choice of coal (UK) versus petrol coke (IT, ES, and FR). Germany outperforms other countries in almost all impact categories due to its lower reliance on fossil fuels in clinker manufacturing, except for the EP indicator, which exhibits a higher average impact (33% more kg Peq than the second worst country) possibly linked to the use of lignite (20% of Germany's total fuel mix, with associated spoil leachate from lignite mining). Despite similar fossil fuel consumption in the UK and France (50% to 55%), differences in KEPIs such as ODP, PM, and POCP underscore the influence of fuel types and additional factors, such as impregnated sawdust use in France.

3.2.2. Cement Environmental Performance

Fig. 9 displays the KEPIs for cement equivalent, with deterministic values from Ecoinvent v3.9 for various cement types included for comparison and validation. Remarkably, there is a good agreement among all indicators.

Examining the cement carbon footprint, similar value ranges are observed for the generated histograms and cement types CEM I, CEM II, and CEM IV. However, CEM III B/C and CEM V/B fall outside the histogram boundaries (discussed in the next section). CEM I, which contains at least 95% clinker, aligns with the upper boundaries of the histogram, consistent with clinker results.

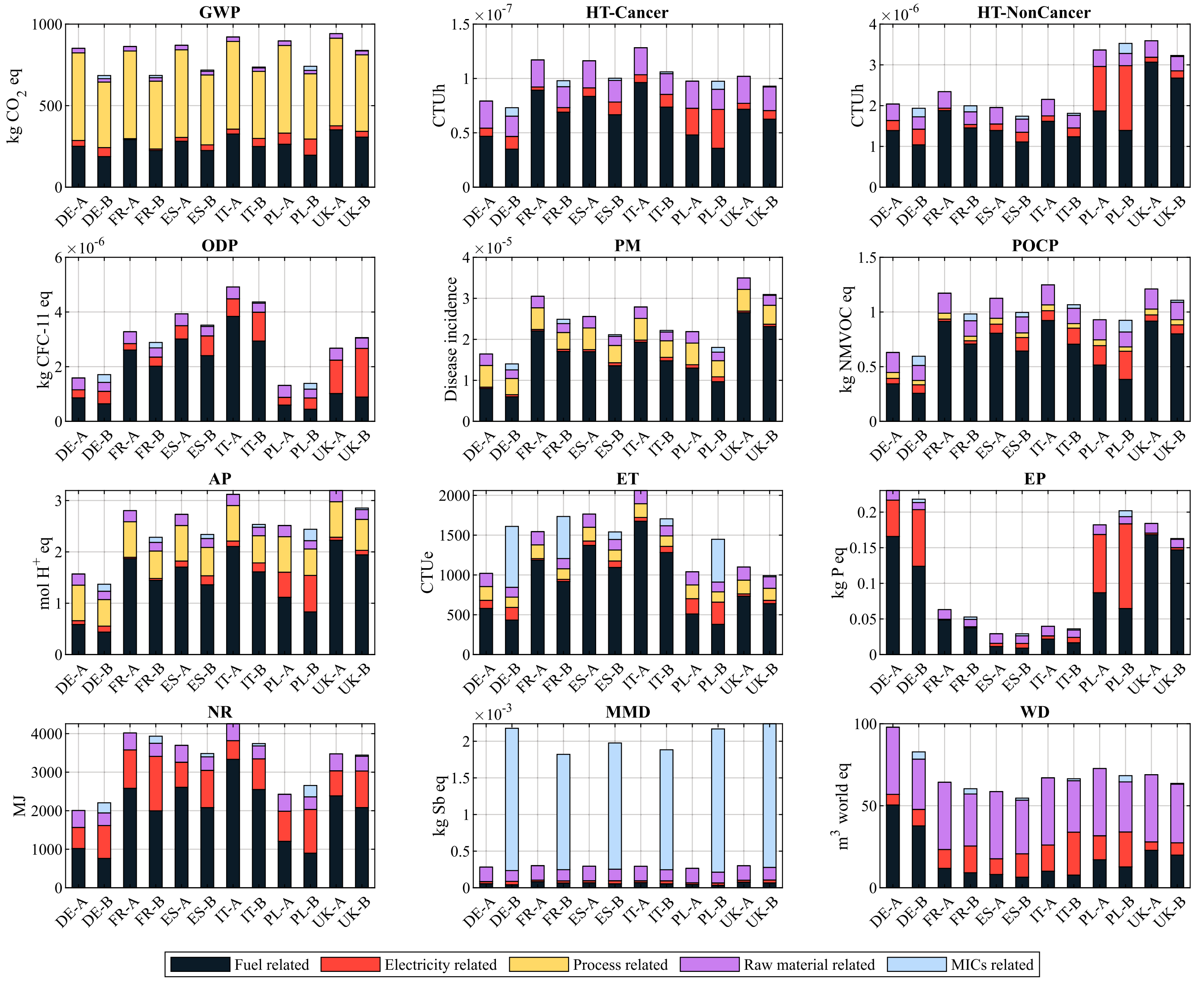


Fig. 8. Contribution analysis to the clinker (A) and cement equivalent (B) average environmental footprint by country.

Country-specific performance mirrors the order seen in clinker manufacturing, but with a lower carbon footprint due to reduced clinker content. Poland is an exception, showing a higher mean and standard deviation than Italy, contrary to the clinker case. This can be attributed to two main reasons. On the one hand, the process-related emissions are diluted by the lower clinker content, making the other emissions more relevant. In addition, the cement manufacturing process consumes more electricity than the clinker. As it was shown before, on average, around 120 kWh of electricity per tonne of cement equivalent is needed, while the clinker consumes 80 kWh/t. On the other hand, Poland's electricity mix uses high amounts of hard coal, making the unitary contribution of the electricity consumption to cement manufacturing 145% more than for the clinker. This fact also explains why Poland is the worst-performing country in terms of the non-carcinogenic human toxicity category.

For the rest of the human-related KEPIs, there's good agreement between the generated stochastic data and Ecoinvent deterministic values. The rule of higher clinker content leading to increased environmental burdens applies here, along with the impact of fossil fuels (both during calcination and the background electricity mix).

Ecosystem quality indicators exhibit reasonable agreement. The AP shows a difference between Germany and the rest of the countries. This disparity arises from variations in unitary acidification impact for different fuels. For example, 1 MJ of hard coal combustion generates almost twelve times more acidification impact (1.1E-3 molH$^+$) than lignite. Germany's reliance on the latter (over 2/3 of the fossil fuel mix), while other countries use a mix of hard coal, petcoke, and heavy fuel oil, explains the observed difference in AP. This pattern reverses in EP, where 1 MJ from lignite is 2.15 times worse than the second-highest source, hard coal.

Finally, resource depletion-related KEPIs show exceptional agreement between the calculated benchmark and the different cement types. In particular, the metals and minerals depletion potential exhibits all deterministic values in the central range of the generated histograms.

3.2.3. Clinker factor and EPDs benchmark

This section assesses the agreement between the simulated stochastic KEPIs and information from the EPD database. Using 10000 randomly generated cement equivalent compositions based on the calibrated model distributions for different countries (Table 4), KEPIs are calculated, and results are organised by decreasing clinker factor. The optimal front for each country, highlighting the best-performing result in each 1% interval, is presented in Fig. 10. Only EPDs generated with

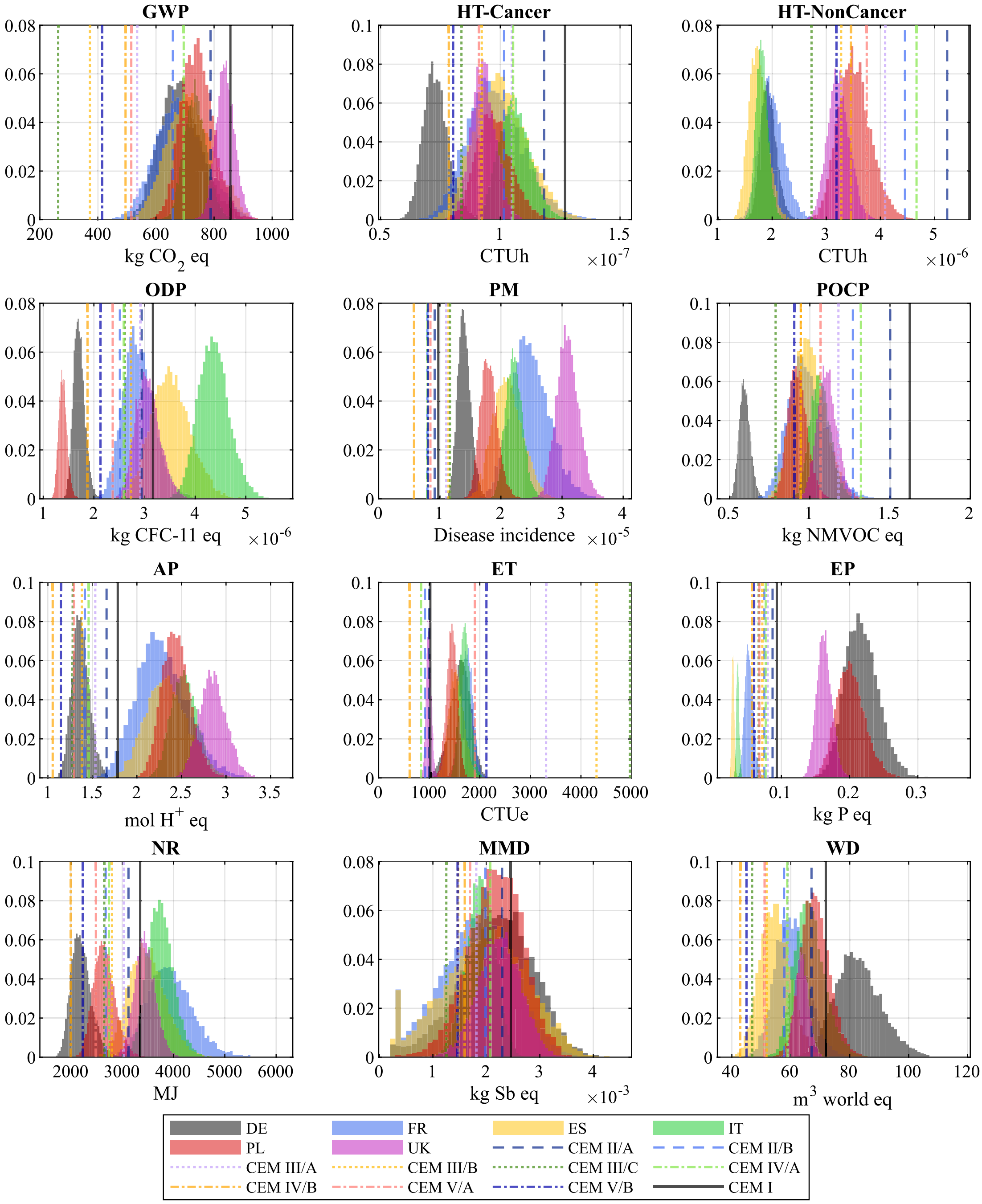


Fig. 9. Histograms of cement equivalent KEPIs in Europe, 2020.

the same impact methodology and falling within a reasonable range are displayed for clarity.

Fig. 10 reveals a decreasing trend in most KEPIs with the reduction of the clinker factor. However, an optimal threshold exists where the benefits of reducing clinker are outweighed by the burdens of MICs. This threshold varies by country and the specific KEPI considered.

The climate change indicator benefits most from reduced clinker content, exhibiting a linearly decreasing trend across all countries. A 1% reduction in clinker reflects an abatement of 7 kg CO_{2eq} for DE, FR, ES, and PL and 8.5 to 9.3 kg CO_{2eq} for UK and IT, respectively. Notably, there is strong agreement between this study and EPDs within the 40% to 95% clinker content range. However, discrepancies below the 40% ratio may arise from data incompleteness in histogram calculations or EPDs' lack of representativeness for the current volume of cement manufacturing in Europe.

Concerning human health-related impacts, the advantages of reducing clinker content are not immediately evident. A critical point emerges where further clinker replacement by MICs becomes counterproductive. For instance, countries with high Ground Granulated Blast Furnace Slag (GGBFS) usage, such as Germany, France, and Poland, show a sharp increase in ET indicator with greater clinker replacement (in contrast to the decreasing trend in other countries using different MICs), related to the hydrogen sulphide emission during the quenching of the slag. The agreement between simulated values and EPDs is limited, with significant variability in the disclosed values.

Italy stands out with the most substantial decrease in impact slope among different indicators, signalling high improvement potential.

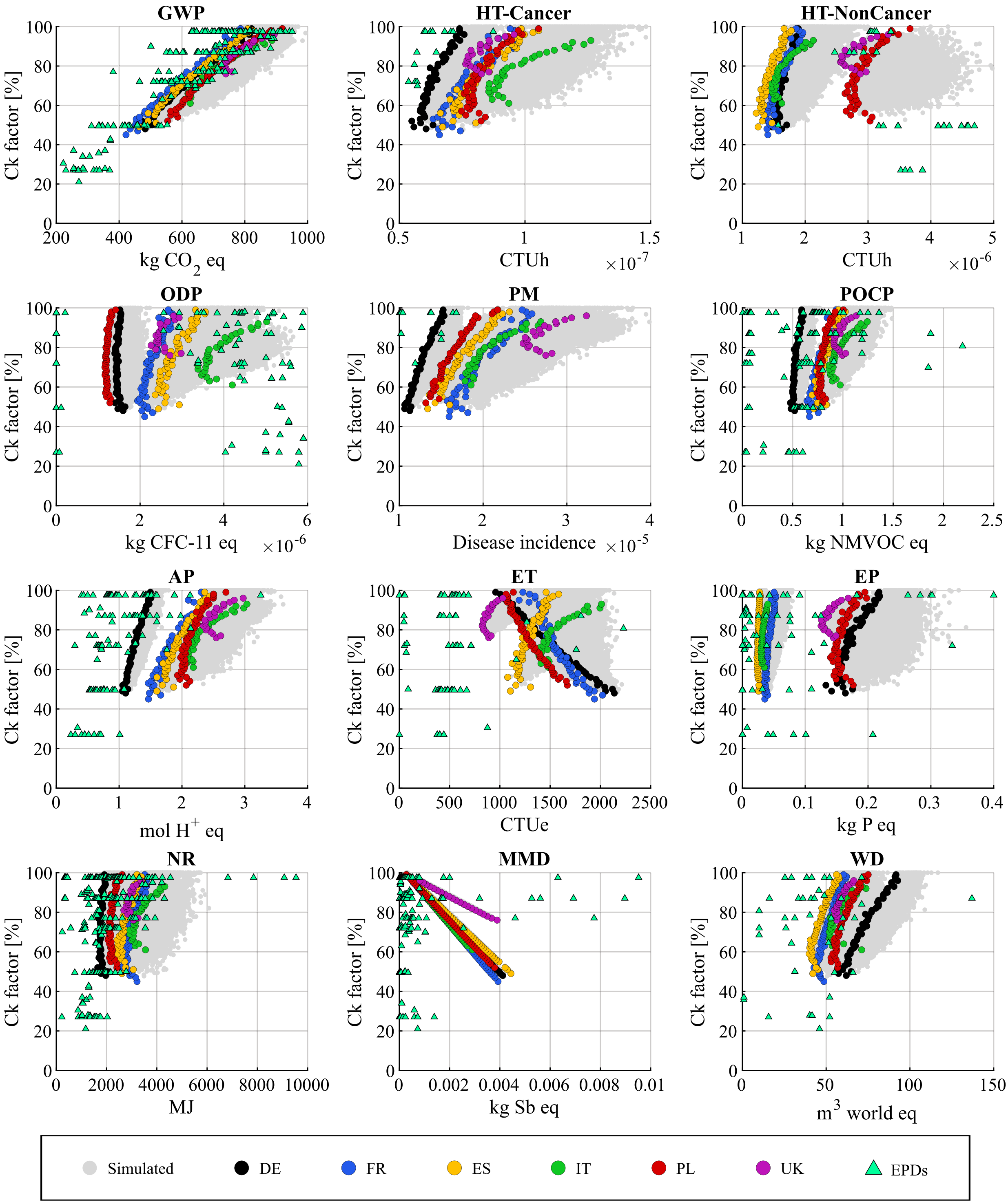


Fig. 10. Comparison between LCA simulated results and EPDs for cement KEPIs as a function of the clinker factor.

These findings emphasise that clinker replacement with limestone is a highly efficient strategy for reducing the environmental footprint of cement.

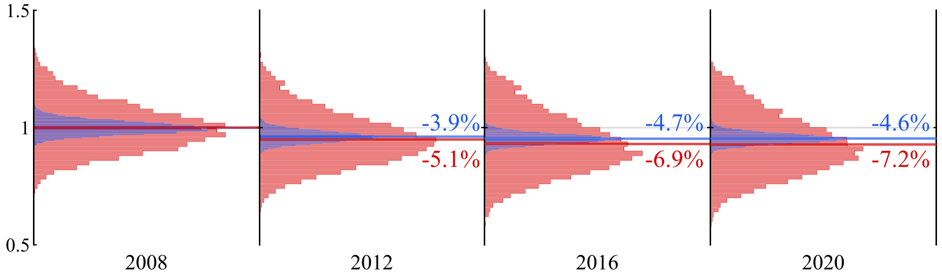
Similar to previous analyses, the non-renewable energy depletion indicator aligns well between this study and the disclosed data. Examining metals and minerals depletion reveals a seemingly linear relationship with clinker replacement, influenced by gypsum, fly ash, and, in a lesser amount, slag usage. Furthermore, the electricity mix also plays a significant role, as depicted in Fig. 8.

3.2.4. *Temporal evolution*

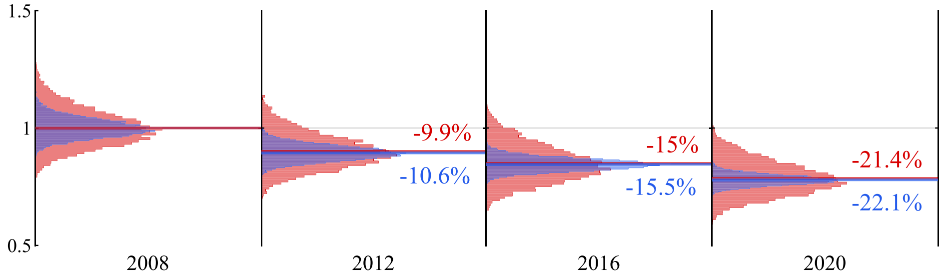
Fig. 6 shows the statistical evolution of Germany's clinker and cement manufacturing parameters. It can be seen that from 2008 until today, there has been a trend in the reduction of the clinker's energy intensity, probably linked to an increase in the efficiency of the kilns. However, it is also possible to see an increase in terms of both electricity consumption and mean clinker content.

Fig. 11 illustrates the temporal evolution of GWP, ET, and NR for clinker and cement equivalent manufacturing in Germany from 2008 and 2020. The complete data for other indicators is available in the

(a) GWP



(b) AP



(c) NR

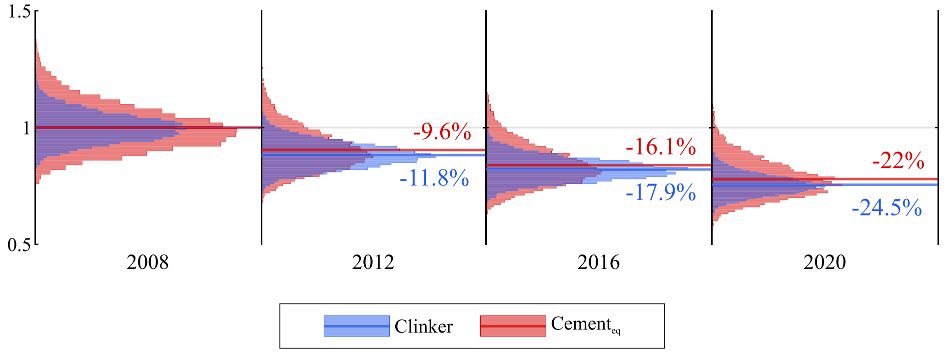


Fig. 11. Time evolution LCA results for three clinker and cement KEPIs in Germany, 2008 to 2020. (a) GWP; (b) AP; (c) NR.

supplementary file. The average histogram value is highlighted, and the relative performance against 2008 is displayed.

Notably, there is a higher degree of variability in cement's environmental performance compared to clinker, consistent with observations in the previous section. This variability is attributed to fluctuations in electricity consumption and clinker content. The CO_2 footprint consistently improves over the years, reaching 4.6% and 7.2% reductions for clinker and cement, respectively, compared to 2008. This improvement is linked to the reduced energy requirements in clinker manufacturing and the decreased use of fossil fuels. The NR indicator exhibits clear improvement, with a total reduction of 24.5% and 22%, showing the highest cutback between 2008 and 2012, followed by a diminishing pace (6.5% and 5.9%). However, there is a growth in the variability of cement performance, mainly due to increased variability in clinker content.

The AP indicator, reflecting the ecosystem impact, shows a noticeable reduction in 2012, 2016, and 2020, potentially attributed to decreased use of slag and fossil fuels in cement and clinker manufacturing.

4. Limitations and future research

The established benchmarks are tailored to a specific subset of European countries, showcasing a remarkable depth of comprehensive data. When undertaking comparisons between the current research-involved countries and those on a European or even non-European scale, caution should be exercised. This entails ensuring that the completeness of the datasets being compared is equal, thus fostering a more accurate and meaningful analysis. Moreover, data gaps will inevitably introduce some degree of bias in the results. The benchmarks demonstrated robustness across all countries, except for PL and the UK in particular KEPIs indicators, as explained before, stressing the importance of data completeness.

The subsequent identification of research gaps serves as an initial foundation for future investigations. There is an imperative need for the creation of global stochastic benchmarks to facilitate the sustainable development of the cement industry. Nevertheless, it's crucial to acknowledge that the challenge persists in collecting comprehensive global data. A deeper investigation regarding the use of different mineral additions to clinker and their impact on the environmental benchmarks should be explored. Moreover, new performance-based KEPIs are needed for a comprehensive comparison of different cementitious materials. Economic assessment can also be included in combination with stochastic indicators. Additionally, the effect of emerging manufacturing technologies, such as carbon capture and storage or utilisation, needs to be further assessed. Finally, the development of a stochastic-based framework for the judgement of EPDs could greatly benefit the cement industry in its path towards more sustainable materials.

5. Conclusions

This study delves into the environmental footprints of clinker and cement in Europe, employing a robust LCA methodology. The investigation begins with industry-reported data, paving the way for the development of a stochastic benchmark encompassing six European countries that collectively contribute over 75% of European cement manufacturing. This benchmark undergoes a meticulous validation process against background environmental datasets from Ecoinvent, supplemented by the analysis and comparison of over 300 EPDs. The culmination of these efforts yields a wealth of insights and significant conclusions across various dimensions.

Regarding clinker and cement manufacturing:

- In the realm of clinker and cement manufacturing, the study underscores the potency of clinker reduction or replacement as a highly effective measure for curbing cement-related GHG emissions. This reduction exhibits a notable pace, amounting to 7 to 9 kg CO_{2eq}/t for each 1% reduction. However, it can lead to an increase in other environmental burdens, depending on the mineral component used as a replacement. The search for low-carbon binder alternatives will need to account for a holistic environmental impact analysis. Calcine clays may, in this aspect, be a promising solution.
- A significant agreement is observed among the developed histograms, the Ecoinvent database, and producer-published EPDs concerning the CO_2 footprint of cements in Europe. However, the study acknowledges the need for sustained efforts to achieve a similar level of confidence across various Key Environmental Performance Indicators (KEPIs). Notably, the study exposes a considerable dispersion in results, particularly in terms of damage to ecosystems and biodiversity.
- The adoption of country-specific benchmarks, as opposed to industry averages from background environmental databases such as Ecoinvent, enhances accuracy and reliability. This approach demonstrates a remarkable reduction in result variability, ranging from 2 to 7 times the standard deviation across all KEPIs. The methodology's adaptability to any particular country or region positions it as a powerful tool for producers, manufacturers, and consumers to measure and track the environmental performance of construction products.
- The study identifies the reduction in energy intensity in cement manufacturing as a strategic pathway towards achieving overall enhanced environmental performance. A temporal analysis of Germany's industry substantiates the efficacy of this approach, suggesting potential exploration into low-energy binder production, such as belite cement.

From a country-specific perspective:

- Italy and the UK stand out as beneficiaries of a 10 to 20% reduction in average clinker content in their cement equivalent mix. This reduction not only impacts the national Green House Gas (GHG) emissions profile positively but also mitigates damage to human health, ecosystems, and non-renewable resource depletion. However, the study cautions that the potential of this measure in the UK is contingent on a shift to a less fossil-intensive electricity mix.
- Poland emerges as a country with significant potential to reduce its cement environmental footprint through a shift to a renewable electricity mix, such as wind energy. However, this transformation is anticipated to decrease the availability of fly ash, leading to potential environmental impacts if replaced by slag.
- Germany showcases global leadership in both clinker and cement production, consistently exhibiting the lowest or second-lowest environmental impact across various indicators. Notably, Germany's performance in terms of CO_{2eq} emissions, human toxicity (HT), ozone depletion potential (ODP), particulate matter (PM), photochemical ozone creation potential (POCP), acidification potential (AP), ecotoxicity (ET), non-renewable resource depletion (NR), and metal depletion (MMD) outshines other countries. However, Germany faces challenges, particularly in terms of eutrophication potential (EP) and water depletion potential (WDP), indicating the need for targeted improvement strategies.

For designers of EPDs:

- The study highlights a scarcity of agreement between disclosed information and industry-related data, particularly for impact categories beyond climate change. The inclusion of variability-related information, such as the standard deviation of calculated values, is advocated to enhance designers' understanding of construction materials' impact.
- The study positions itself as a benchmark for various stakeholders, serving manufacturers, designers, and policymakers. It emphasises the importance of using supplier-specific information for intermediate consumers, highlighting its direct impact on product environmental performance. Additionally, the study underscores the pitfalls of relying on background data, which can introduce substantial variability in results, compromising assessment quality and reliability.

To wrap up, the research lends support to the use of stochastic information for EPD disclosure, drawing a parallel with specifying the compressive strength of concrete. Acknowledging and addressing uncertainty is deemed crucial for accurate building environmental assessments, aligning with the industry's quest for transparent and uncertainty-aware environmental evaluations.

Declaration of competing interest

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

Data availability

For closer analysis (or reproduction), the research data collected and generated in this work can be found at https://doi.org/10.5281/zenodo.10362042.

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Appendix A. Calibrated distribution results

Figs. A.12 to A.15 show the raw extracted data from the industry reports together with the calibrated PDFs shown in Table 4.

Appendix B. Sensitivity of the parameter calibration

Figs. B.16 to B.19 show the different fitting curves obtained when applying the filling methods described in the methodology section. Additionally, the influence of the different approaches in the PDFs parameters and the KEPIs is shown in Tables B.6, B.7 and B.8.

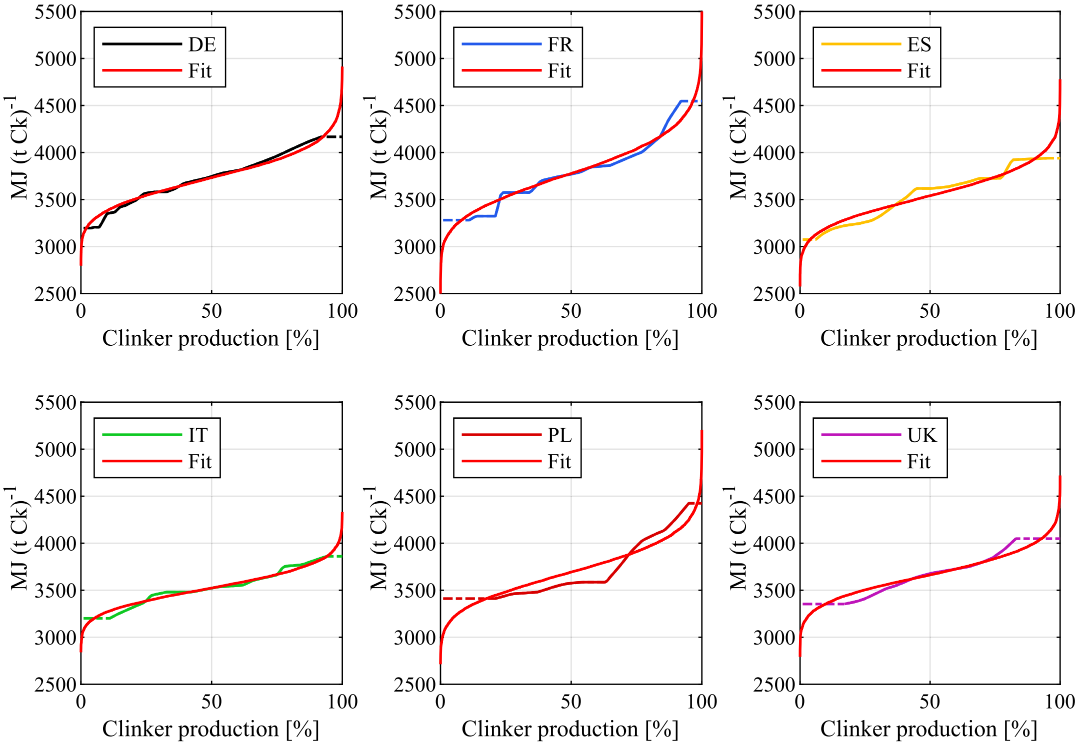

Fig. A.12. PDFs calibrated into raw data: Clinker energy intensity.

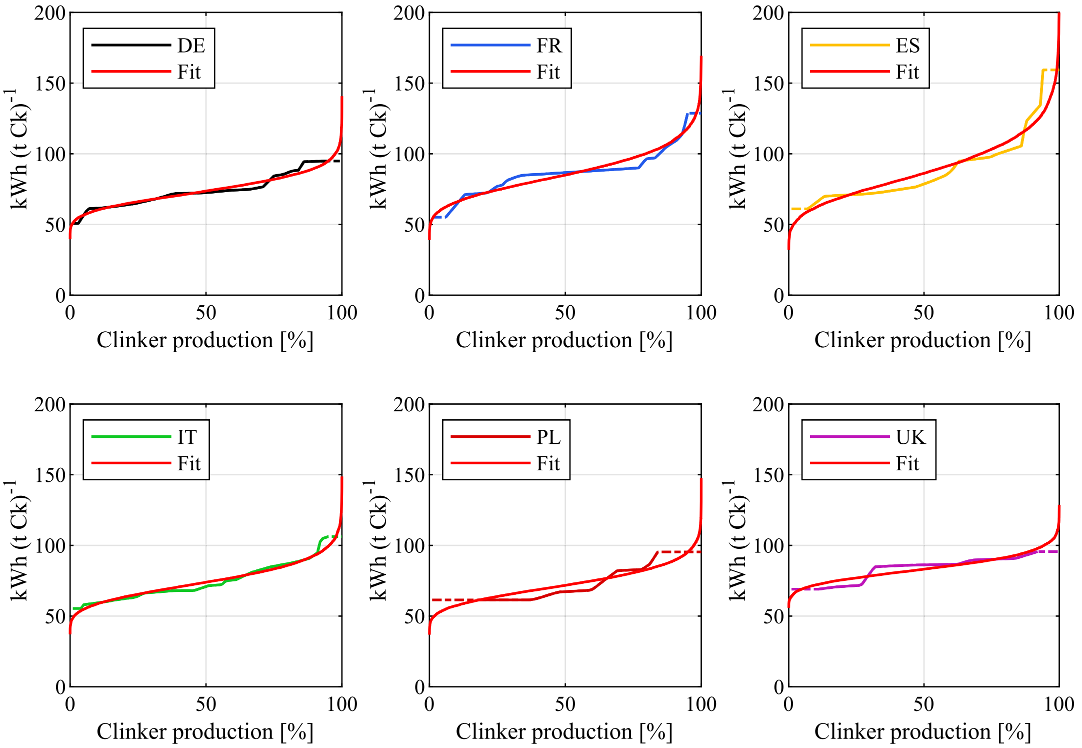

Fig. A.13. PDFs calibrated into raw data: Clinker power intensity.

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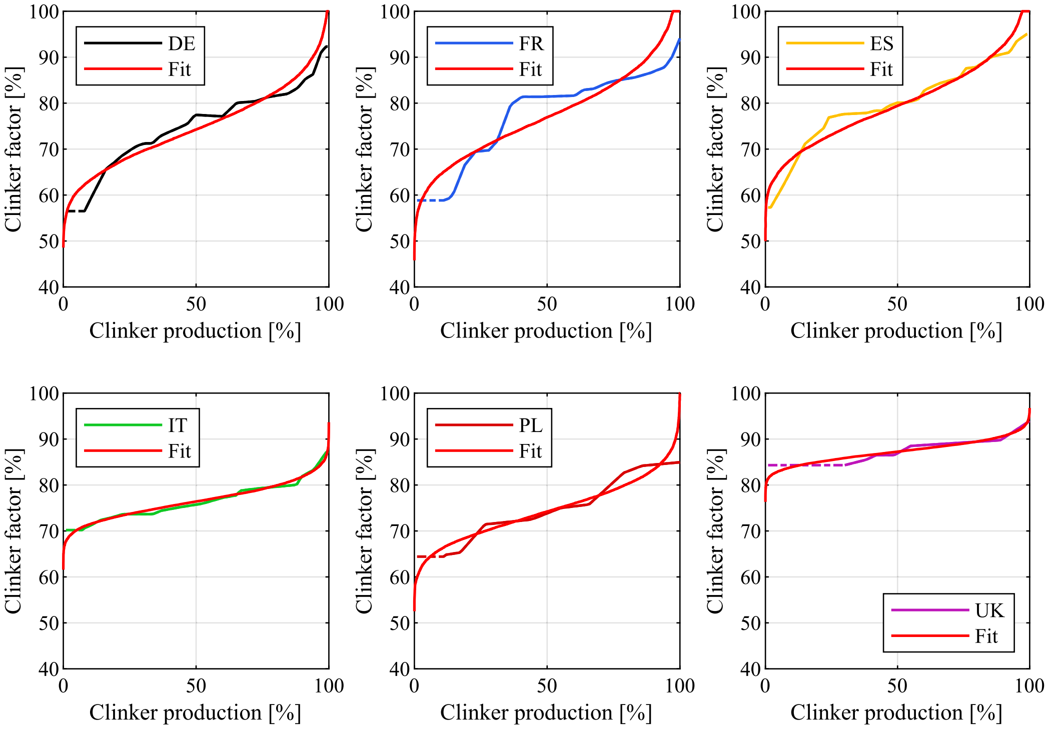
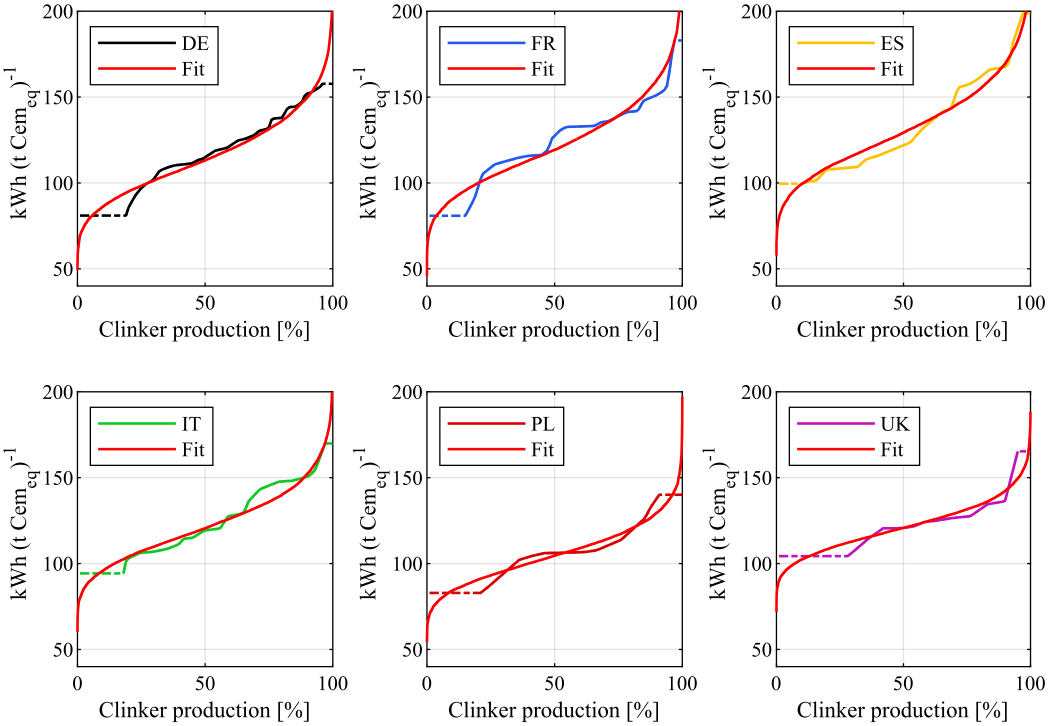


Fig. A.14. PDFs calibrated into raw data: Cem clinker factor.



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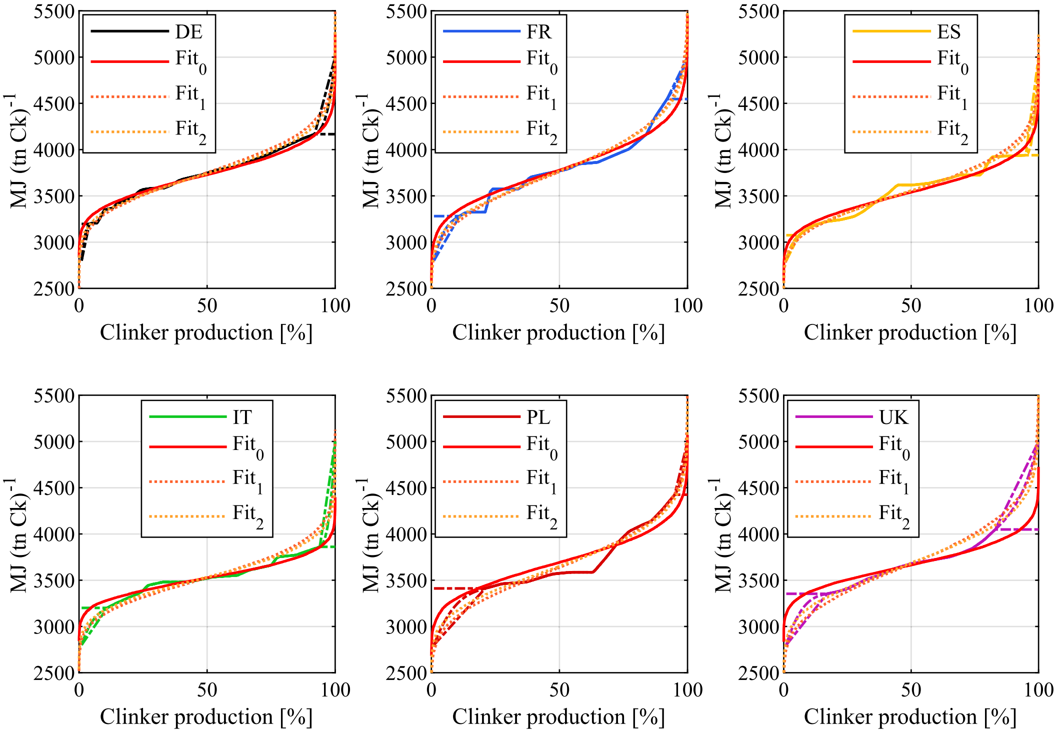

Fig. B.16. PDFs calibrated with different filling methods: Clinker energy intensity.

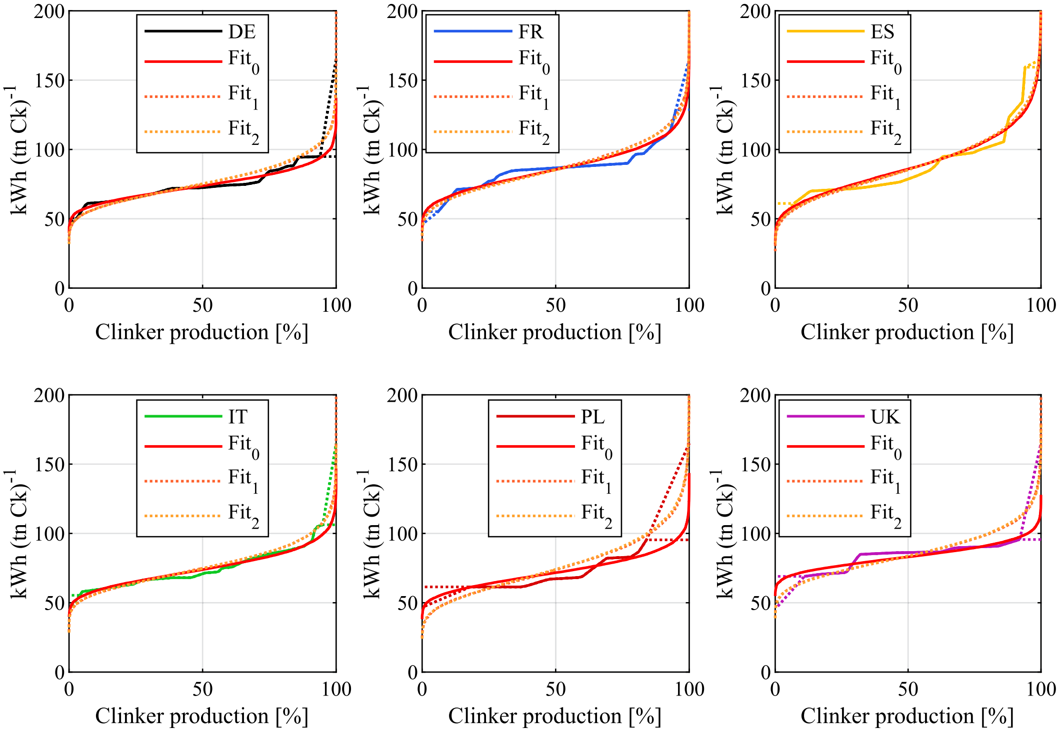

Fig. B.17. PDFs calibrated with different filling methods: Clinker power intensity.

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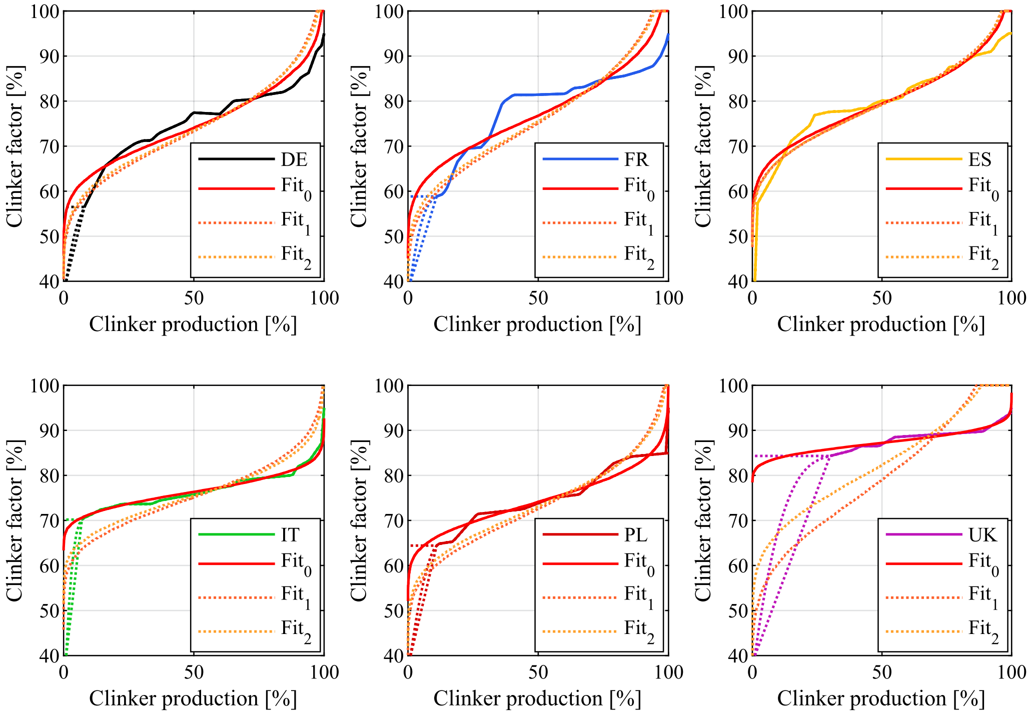

Fig. B.18. PDFs calibrated with different filling methods: Cem clinker factor.

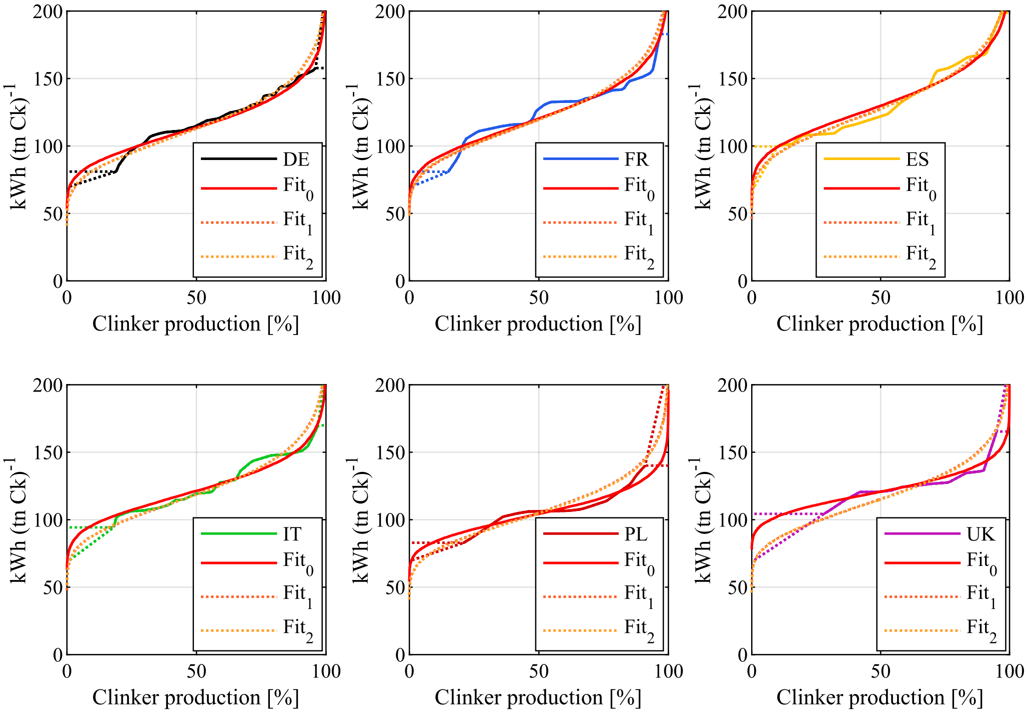

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Table B.6

PDF parameters obtained for different filling methods.

		Fit_0: Original						Fit_1: linear interpolation						Fit_2: cubic interpolation					
Input	**Parameter**	**DE**	**FR**	**ES**	**IT**	**PL**	**UK**	**DE**	**FR**	**ES**	**IT**	**PL**	**UK**	**DE**	**FR**	**ES**	**IT**	**PL**	**UK**
Energy intensity - clinker	μ	8.224	8.238	8.172	8.168	8.214	8.207	8.230	8.233	8.177	8.170	8.198	8.212	8.228	8.236	8.175	8.169	8.204	8.213
[MJ/ton ck]	σ	0.0770	0.0992	0.0805	0.0579	0.0863	0.0678	0.0999	0.1229	0.1017	0.0946	0.1216	0.1263	0.0929	0.1176	0.0955	0.0841	0.1108	0.1105
Power intensity - clinker	μ	4.299	4.445	4.455	4.303	4.273	4.420	4.318	4.448	4.448	4.314	4.302	4.427	4.318	4.448	4.448	4.314	4.302	4.427
[kWh/ton ck]	σ	0.1585	0.1968	0.2574	0.1801	0.1706	0.1123	0.2118	0.2256	0.2742	0.2221	0.2969	0.2074	0.2118	0.2256	0.2742	0.2221	0.2969	0.2074
Clinker factor	μ	4.307	4.340	4.375	4.336	4.308	4.469	4.294	4.320	4.371	4.318	4.284	4.370	4.297	4.327	4.371	4.324	4.290	4.414
[% ck]	σ	0.1259	0.1383	0.1196	0.0525	0.0911	0.0305	0.1621	0.1866	0.1341	0.1144	0.1521	0.2129	0.1552	0.1716	0.1341	0.0987	0.1408	0.1582
Power intensity - cement	μ	4.732	4.788	4.864	4.799	4.647	4.794	4.726	4.780	4.849	4.778	4.652	4.750	4.726	4.780	4.849	4.778	4.652	4.750
[kWh/ton cem]	σ	0.2157	0.2239	0.2094	0.1813	0.1678	0.1295	0.2537	0.2506	0.2410	0.2341	0.2425	0.2257	0.2537	0.2506	0.2410	0.2341	0.2425	0.2257

Table B.7

Clinker KEPIs for different filling methods.

		DE			FR			ES			IT			PL			UK		
		Fit_0	Fit_1	Fit_2	Fit_0	Fit_1	Fit_2	Fit_0	Fit_1	Fit_2	Fit_0	Fit_1	Fit_2	Fit_0	Fit_1	Fit_2	Fit_0	Fit_1	Fit_2
AP	μ	1.57E+00	1.58E+00	1.58E+00	2.81E+00	2.80E+00	2.80E+00	2.73E+00	2.74E+00	2.74E+00	3.12E+00	3.13E+00	3.13E+00	2.51E+00	2.53E+00	2.53E+00	3.20E+00	3.22E+00	3.22E+00
[mol H+ eq]	σ	4.68E-02	6.09E-02	5.73E-02	1.86E-01	2.31E-01	2.21E-01	1.40E-01	1.77E-01	1.67E-01	1.24E-01	2.03E-01	1.80E-01	1.28E-01	2.08E-01	2.00E-01	1.51E-01	2.87E-01	2.50E-01
GWP	μ	8.52E+02	8.55E+02	8.54E+02	8.63E+02	8.63E+02	8.63E+02	8.70E+02	8.72E+02	8.72E+02	9.21E+02	9.23E+02	9.23E+02	8.96E+02	8.98E+02	8.99E+02	9.41E+02	9.46E+02	9.46E+02
[kg CO2 eq]	σ	2.02E+01	2.63E+01	2.48E+01	2.90E+01	3.60E+01	3.44E+01	2.35E+01	2.94E+01	2.78E+01	1.98E+01	3.20E+01	2.85E+01	2.55E+01	3.87E+01	3.65E+01	2.40E+01	4.56E+01	3.99E+01
ET	μ	1.02E+03	1.03E+03	1.03E+03	1.55E+03	1.54E+03	1.54E+03	1.76E+03	1.77E+03	1.77E+03	2.06E+03	2.07E+03	2.07E+03	1.04E+03	1.05E+03	1.05E+03	1.10E+03	1.11E+03	1.11E+03
[CTUe]	σ	4.76E+01	6.21E+01	5.89E+01	1.18E+02	1.47E+02	1.40E+02	1.11E+02	1.41E+02	1.32E+02	9.80E+01	1.61E+02	1.43E+02	5.49E+01	8.76E+01	8.38E+01	4.99E+01	9.48E+01	8.26E+01
NRE	μ	2.01E+03	2.03E+03	2.03E+03	4.02E+03	4.03E+03	4.03E+03	3.70E+03	3.71E+03	3.71E+03	4.26E+03	4.28E+03	4.28E+03	2.42E+03	2.46E+03	2.46E+03	3.48E+03	3.52E+03	3.52E+03
[MJ]	σ	1.18E+02	1.57E+02	1.55E+02	3.24E+02	3.95E+02	3.80E+02	2.71E+02	3.19E+02	3.09E+02	2.14E+02	3.38E+02	3.04E+02	1.70E+02	2.93E+02	2.85E+02	1.78E+02	3.36E+02	3.03E+02
EP	μ	2.30E-01	2.33E-01	2.33E-01	6.31E-02	6.31E-02	6.31E-02	2.92E-02	2.93E-02	2.93E-02	3.98E-02	4.00E-02	3.99E-02	1.82E-01	1.86E-01	1.86E-01	1.84E-01	1.86E-01	1.86E-01
[kg P eq]	σ	1.52E-02	1.99E-02	1.92E-02	4.83E-03	6.00E-03	5.73E-03	1.48E-03	1.67E-03	1.64E-03	1.52E-03	2.33E-03	2.12E-03	1.59E-02	2.87E-02	2.81E-02	1.14E-02	2.17E-02	1.89E-02
HT-Cancer	μ	7.93E-08	7.98E-08	7.97E-08	1.17E-07	1.17E-07	1.17E-07	1.16E-07	1.17E-07	1.17E-07	1.28E-07	1.29E-07	1.29E-07	9.74E-08	9.85E-08	9.86E-08	1.02E-07	1.03E-07	1.03E-07
[CTUh]	σ	3.81E-09	4.96E-09	4.69E-09	8.90E-09	1.11E-08	1.05E-08	7.02E-09	8.78E-09	8.30E-09	5.77E-09	9.36E-09	8.33E-09	5.91E-09	9.89E-09	9.56E-09	4.90E-09	9.31E-09	8.13E-09
HT-NonCancer	μ	2.04E-06	2.06E-06	2.06E-06	2.34E-06	2.34E-06	2.34E-06	1.95E-06	1.96E-06	1.96E-06	2.15E-06	2.16E-06	2.16E-06	3.36E-06	3.41E-06	3.41E-06	3.59E-06	3.63E-06	3.63E-06
[CTUh]	σ	1.14E-07	1.49E-07	1.41E-07	1.87E-07	2.33E-07	2.22E-07	1.19E-07	1.48E-07	1.41E-07	9.74E-08	1.58E-07	1.41E-07	2.47E-07	4.21E-07	4.09E-07	2.08E-07	3.96E-07	3.45E-07
MMD	μ	2.82E-04	2.84E-04	2.83E-04	3.02E-04	3.02E-04	3.02E-04	2.94E-04	2.94E-04	2.94E-04	2.93E-04	2.94E-04	2.94E-04	2.65E-04	2.66E-04	2.66E-04	3.01E-04	3.03E-04	3.02E-04
[kg Sb eq]	σ	6.40E-06	8.47E-06	8.35E-06	9.34E-06	1.15E-05	1.10E-05	9.21E-06	1.03E-05	1.02E-05	6.16E-06	8.89E-06	8.32E-06	5.50E-06	9.11E-06	8.79E-06	6.03E-06	1.14E-05	1.04E-05
ODP	μ	1.59E-06	1.60E-06	1.60E-06	3.28E-06	3.28E-06	3.28E-06	3.93E-06	3.95E-06	3.95E-06	4.92E-06	4.95E-06	4.94E-06	1.31E-06	1.33E-06	1.33E-06	2.68E-06	2.72E-06	2.72E-06
[kg CFC-11 eq]	σ	8.16E-08	1.07E-07	1.04E-07	2.64E-07	3.28E-07	3.12E-07	2.74E-07	3.34E-07	3.19E-07	2.53E-07	3.96E-07	3.58E-07	7.08E-08	1.17E-07	1.13E-07	1.54E-07	2.89E-07	2.87E-07
PM	μ	1.64E-05	1.65E-05	1.65E-05	3.05E-05	3.05E-05	3.05E-05	2.56E-05	2.57E-05	2.57E-05	2.79E-05	2.80E-05	2.80E-05	2.19E-05	2.18E-05	2.18E-05	3.50E-05	3.53E-05	3.53E-05
[Disease incidence]	σ	6.20E-07	8.08E-07	7.55E-07	2.19E-06	2.73E-06	2.60E-06	1.37E-06	1.74E-06	1.63E-06	1.13E-06	1.85E-06	1.64E-06	1.13E-06	1.58E-06	1.46E-06	1.80E-06	3.42E-06	2.98E-06
POCP	μ	6.30E-01	6.34E-01	6.33E-01	1.17E+00	1.17E+00	1.17E+00	1.13E+00	1.13E+00	1.13E+00	1.25E+00	1.25E+00	1.25E+00	9.28E-01	9.34E-01	9.35E-01	1.21E+00	1.22E+00	1.22E+00
[kg NMVOC eq]	σ	2.77E-02	3.61E-02	3.40E-02	9.11E-02	1.13E-01	1.08E-01	6.84E-02	8.52E-02	8.07E-02	5.63E-02	9.06E-02	8.09E-02	5.38E-02	8.47E-02	8.07E-02	6.25E-02	1.19E-01	1.04E-01
WD	μ	9.79E+01	9.85E+01	9.84E+01	6.44E+01	6.44E+01	6.44E+01	5.87E+01	5.86E+01	5.86E+01	6.71E+01	6.74E+01	6.74E+01	7.27E+01	7.35E+01	7.34E+01	6.90E+01	6.94E+01	6.93E+01
[m3 world eq]	σ	4.03E+00	5.25E+00	4.94E+00	2.57E+00	3.04E+00	2.99E+00	2.61E+00	2.76E+00	2.75E+00	2.97E+00	3.78E+00	3.77E+00	2.92E+00	5.21E+00	5.10E+00	1.65E+00	3.13E+00	2.80E+00

Table B.8
Cement KEPIs for different filling methods.

		DE			FR			ES			IT			PL			UK		
		Fit_0	Fit_1	Fit_2	Fit_0	Fit_1	Fit_2	Fit_0	Fit_1	Fit_2	Fit_0	Fit_1	Fit_2	Fit_0	Fit_1	Fit_2	Fit_0	Fit_1	Fit_2
AP	μ	1.37E+00	1.25E-01	1.19E-01	2.29E+00	3.55E-01	3.30E-01	2.34E+00	2.69E-01	2.65E-01	2.53E+00	2.86E-01	2.50E-01	2.44E+00	2.40E-01	2.32E-01	2.86E+00	4.73E-01	3.97E-01
[mol H+ eq]	σ	9.98E-02	1.25E-01	1.19E-01	2.84E-01	3.55E-01	3.30E-01	2.41E-01	2.69E-01	2.65E-01	1.51E-01	2.86E-01	2.50E-01	1.60E-01	2.40E-01	2.32E-01	1.54E-01	4.73E-01	3.97E-01
GWP	μ	6.86E+02	9.02E+01	8.62E+01	6.86E+02	1.08E+02	1.00E+02	7.19E+02	8.59E+01	8.57E+01	7.36E+02	7.88E+01	6.90E+01	7.42E+02	8.62E+01	8.13E+01	8.39E+02	1.33E+02	1.09E+02
[kg CO2 eq]	σ	7.24E+01	9.02E+01	8.62E+01	8.61E+01	1.08E+02	1.00E+02	7.83E+01	8.59E+01	8.57E+01	3.90E+01	7.88E+01	6.90E+01	5.48E+01	8.62E+01	8.13E+01	3.20E+01	1.33E+02	1.09E+02
ET	μ	1.61E+03	2.54E+02	2.45E+02	1.73E+03	1.55E+02	1.47E+02	1.54E+03	1.71E+02	1.66E+02	1.70E+03	1.86E+02	1.63E+02	1.45E+03	1.61E+02	1.52E+02	9.93E+02	1.56E+02	1.31E+02
[CTUe]	σ	2.04E+02	2.54E+02	2.45E+02	1.27E+02	1.55E+02	1.47E+02	1.49E+02	1.71E+02	1.66E+02	1.02E+02	1.86E+02	1.63E+02	1.03E+02	1.61E+02	1.52E+02	5.10E+01	1.56E+02	1.31E+02
NRE	μ	2.21E+03	2.35E+02	2.35E+02	3.94E+03	5.20E+02	5.03E+02	3.48E+03	4.12E+02	4.07E+02	3.74E+03	4.27E+02	3.85E+02	2.65E+03	3.10E+02	3.05E+02	3.44E+03	4.91E+02	4.28E+02
[MJ]	σ	1.98E+02	2.35E+02	2.35E+02	4.43E+02	5.20E+02	5.03E+02	3.64E+02	4.12E+02	4.07E+02	2.53E+02	4.27E+02	3.85E+02	2.09E+02	3.10E+02	3.05E+02	1.99E+02	4.91E+02	4.28E+02
EP	μ	2.18E-01	3.05E-02	2.96E-02	5.28E-02	7.78E-03	7.24E-03	2.92E-02	2.13E-03	2.13E-03	3.61E-02	3.36E-03	3.07E-03	2.02E-01	3.18E-02	3.14E-02	1.63E-01	3.04E-02	2.58E-02
[kg P eq]	σ	2.50E-02	3.05E-02	2.96E-02	6.26E-03	7.78E-03	7.24E-03	1.89E-03	2.13E-03	2.13E-03	2.04E-03	3.36E-03	3.07E-03	2.13E-02	3.18E-02	3.14E-02	1.11E-02	3.04E-02	2.58E-02
HT-Cancer	μ	7.32E-08	6.69E-09	6.40E-09	9.81E-08	1.46E-08	1.36E-08	1.00E-07	1.25E-08	1.22E-08	1.06E-07	1.23E-08	1.08E-08	9.74E-08	1.11E-08	1.08E-08	9.30E-08	1.50E-08	1.26E-08
[CTUh]	σ	5.38E-09	6.69E-09	6.40E-09	1.17E-08	1.46E-08	1.36E-08	1.11E-08	1.25E-08	1.22E-08	6.70E-09	1.23E-08	1.08E-08	7.38E-09	1.11E-08	1.08E-08	5.01E-09	1.50E-08	1.26E-08
HT-NonCancer	μ	1.94E-06	1.83E-07	1.76E-07	2.00E-06	2.80E-07	2.61E-07	1.74E-06	1.94E-07	1.90E-07	1.81E-06	2.01E-07	1.77E-07	3.53E-06	4.56E-07	4.47E-07	3.23E-06	5.67E-07	4.82E-07
[CTUh]	σ	1.48E-07	1.83E-07	1.76E-07	2.26E-07	2.80E-07	2.61E-07	1.72E-07	1.94E-07	1.90E-07	1.11E-07	2.01E-07	1.77E-07	3.06E-07	4.56E-07	4.47E-07	2.04E-07	5.67E-07	4.82E-07
MMD	μ	2.17E-03	8.74E-04	8.38E-04	1.81E-03	8.77E-04	8.16E-04	1.97E-03	8.42E-04	8.44E-04	1.89E-03	5.72E-04	5.01E-04	2.16E-03	8.05E-04	7.55E-04	2.24E-03	2.16E-03	1.73E-03
[kg Sb eq]	σ	7.01E-04	8.74E-04	8.38E-04	6.98E-04	8.77E-04	8.16E-04	7.68E-04	8.42E-04	8.44E-04	2.69E-04	5.72E-04	5.01E-04	5.04E-04	8.05E-04	7.55E-04	3.99E-04	2.16E-03	1.73E-03
ODP	μ	1.71E-06	1.35E-07	1.33E-07	2.89E-06	3.86E-07	3.62E-07	3.52E-06	4.45E-07	4.37E-07	4.37E-06	5.09E-07	4.63E-07	1.39E-06	1.19E-07	1.16E-07	3.06E-06	4.49E-07	4.29E-07
[kg CFC-11 eq]	σ	1.12E-07	1.35E-07	1.33E-07	3.14E-07	3.86E-07	3.62E-07	3.94E-07	4.45E-07	4.37E-07	3.08E-07	5.09E-07	4.63E-07	8.07E-08	1.19E-07	1.16E-07	2.41E-07	4.49E-07	4.29E-07
PM	μ	1.40E-05	1.37E-06	1.30E-06	2.49E-05	3.94E-06	3.67E-06	2.12E-05	2.75E-06	2.71E-06	2.22E-05	2.62E-06	2.29E-06	1.80E-05	2.15E-06	2.01E-06	3.10E-05	5.47E-06	4.60E-06
[Disease incidence]	σ	1.09E-06	1.37E-06	1.30E-06	3.16E-06	3.94E-06	3.67E-06	2.46E-06	2.75E-06	2.71E-06	1.37E-06	2.62E-06	2.29E-06	1.41E-06	2.15E-06	2.01E-06	1.82E-06	5.47E-06	4.60E-06
POCP	μ	5.96E-01	4.38E-02	4.19E-02	9.83E-01	1.44E-01	1.35E-01	9.97E-01	1.12E-01	1.10E-01	1.07E+00	1.15E-01	1.02E-01	9.24E-01	8.73E-02	8.43E-02	1.11E+00	1.74E-01	1.47E-01
[kg NMVOC eq]	σ	3.52E-02	4.38E-02	4.19E-02	1.16E-01	1.44E-01	1.35E-01	9.92E-02	1.12E-01	1.10E-01	6.46E-02	1.15E-01	1.02E-01	5.90E-02	8.73E-02	8.43E-02	6.19E-02	1.74E-01	1.47E-01
WD	μ	8.30E+01	9.86E+00	9.41E+00	6.05E+01	6.63E+00	6.38E+00	5.46E+01	5.55E+00	5.60E+00	6.65E+01	7.26E+00	7.11E+00	6.84E+01	7.28E+00	7.05E+00	6.36E+01	9.05E+00	7.44E+00
[m3 world eq]	σ	7.91E+00	9.86E+00	9.41E+00	5.55E+00	6.63E+00	6.38E+00	5.05E+00	5.55E+00	5.60E+00	5.14E+00	7.26E+00	7.11E+00	4.74E+00	7.28E+00	7.05E+00	2.30E+00	9.05E+00	7.44E+00

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