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Comparative analysis of available life cycle inventories of cement in the EU

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Abstract

Life cycle inventories are a prerequisite of life-cycle assessments (LCA). This paper conducts a comparative analysis of inventories of several different types of cement produced in Europe. It considers the production of 1 kg of cement from cradle to gate, and all results are based on this mass unit. The reliability of cement inventories is affected by inaccurate or nonrepresentative data, and comparative analysis is difficult due to varying system boundary definitions. Only the four main emissions (CO_2, NOx, SO_2 and dust) are considered. The theoretical model used gives reasonable estimates of emission levels and, thus, can serve as a reference to measured values. In the case of CO_2, this is definitely a feasible alternative to in situ measurements. The emissions derive primarily from the production of clinker, both from the chemical reactions occurring in the kiln and by its fossil fuel consumption.

Keywords: Life-cycle inventory analysis; Cement production; Emissions; System boundary; Clinker

1. Introduction

Life-cycle assessment (LCA) is a method that allows the evaluation of the environmental effects of a product, considering all the stages in its production, from the extraction of resources to the distribution of the ready product or to the processing of the final wastes derived from it [1]. “This includes identifying and quantifying energy and materials used and wastes released to the environment, assessing their environmental impact and evaluating opportunities for improvement” [2]. A prerequisite of an LCA is inventory analysis [1,3]. To achieve this, a life-cycle inventory (LCI) is compiled for each specific product. This is a list of all input and output data associated with that product.

Inventory analysis is the process of compiling the amounts of natural resources and energy taken in by the system and the amount of wastes irretrievably discharged to the environment from the system per functional (or analysis) unit [4]. This LCA step thus identifies and quantifies the inputs from the environment to the system and the outputs from the system to the environment of the product system investigated [5].

The principal objective of this paper is to execute a comparative analysis of inventories associated with the production of different types of cement in Europe (limits: cradle to gate). The reliability of these inventories is thus analysed. The analysis unit is the production of 1 kg of Portland cement or Portland/cementitious blend. Specific cement inventories and data available for the study come from Refs. [6,7] and from the information provided by some cement producers (Table 1).

The feasibility of a comparative analysis is reliant on understanding the data given by each inventory. These values depend on the system boundaries of each production process, which determine what interventions (emissions, wastes or energy consumption) is each manufacturing process responsible for and what interventions

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Table 1
Specific cement inventories studied

Original Nomenclature and Reference	Classification		Clinker (%)	Origin
Cement Portland I [6]	Type I	Portland cement	95–100	Holland
Cement Portland [6]	Type II /A-S	Portland slag cement	80–94	Holland
Blastfurnace slag cement [6]	Type III/B	Blastfurnace cement	20–34	Holland
Cement Hoogoven I [6]	Type III/B	Blastfurnace cement	20–34	Holland
Portland ash cement [6]	Type IV/B	Pozzolanic cement	45–64	Holland
Cement CH [6,8]	Type I	Portland cement	95–100	Switzerland
Cement N [7,9]	Type I	Portland cement	95–100	Sweden
Portland cement NL1 [7,10]	Type I	Portland cement	95–100	Holland
Cement S [7,11]	Type I	Portland cement	95–100	Sweden
Cement SF1 [7,12]	Type I	Portland cement	95–100	Finland
Cement SF2 [7,13]	Type I	Portland cement	95–100	Nordic Countries
Portland cement A [7,14]	Type II/A-S	Portland slag cement	80–94	Austria
Portland cement NL2 [7,15]	Type II/A-S	Portland slag cement	80–94	Holland
Portland cement NL3 [7,16]	Type II/B-S	Portland slag cement	65–79	Holland
Blastfurnace slag cement NL1 [7,15]	Type III/B	Blastfurnace cement	20–34	Holland
Blastfurnace slag cement NL2 [7,16]	Type III/B	Blastfurnace cement	20–34	Holland
'Yleis' cement [17]	Type II/A-M	Portland mix cement	82.2	Finland
'Rapid' cement [17]	Type II/A-LL	Portland limestone cement	90.6	Finland
'Pika' cement [17]	Type I	Portland cement	86.3	Finland
'Mega' cement [17]	Type I	Portland cement	90.7	Finland
'SR' cement [17]	Type I	Portland cement	83.4	Finland

are attributable to the subprocesses, which supply, or are provided by, the main process with a coproduct or service.

2. Cement inventories

LCIs are available for many widely used industrial products, but these seldom correspond to typical construction products, including cement. Comparative inventory analysis is frequently not feasible due to a lack of harmonisation of data format and treatment, inadequate sources of reliable data, unclear definition of system boundaries and nonrepresentative analytical methods with regard to the level of technology used and the geographical setting of the production plant.

To date, only countries well advanced in the environmental LCA field have provided cement inventories. Having to rely on externally produced inventories is thus often inevitable for the other countries, which, within the EU, are responsible for over 85% of cement production in the region [18]. The availability of reliable data is thus scarce, further limited by restricted data access policies sometimes exercised by an industry.

Data provided by technologically advanced factories are not representative, or it cannot always be extrapolated to apply to production in the less advanced production plants. In most countries, however, the availability of reliable cement inventories will tend to increase in line with more widespread environmental awareness of cement production. The intended results of this work could aid a move in this direction.

3. Input data analysis

The information sources studied treat data in one single system, or in two subsystems of clinker production and cement production. The inconvenience of the single system is the difficulty of visualising material and energy flows of the intermediate process steps. A separate treatment of subsystems allows for adjustment to suit specific factory characteristics and adapts the system according to each cement type produced. The main difficulty encountered in the comparative data analysis is due to the different data presentation formats encountered in the inventories. The inventories analysed in this paper come from different sources. They consider different system boundaries and use varying data acquisition methods.

3.1. Raw material consumption

Table 2 is a summary of the raw material consumption for the production of 1 kg of cement as complied from the inventory data sheets. This represents typical data. It is inconsistent; for some cements, the sum of relative amount of components is equal to more than one. There are errors in the data sources. Numerical errors are also likely. Nevertheless, a logical dispersion of input data corresponding to each cement type is evident, although some different system boundaries exist. For example, some inventories include explosives used at the quarries (Portland cement A and Cement S), whilst the rest have not included this material input within their boundaries. Data scatter can also be seen where water consumption is included in the process data or not.

Table 2
Raw material consumption for the production of 1 kg of cement

Original nomenclature	Raw material consumption (kg)										
	Clinker production							Cement production			
	Water	Limestone	Loam/marl	Clay	Chalk	Iron oxides	Other	Clinker	Slag	Fly ashes	Gypsum
Cement Portland I	–	–	1.600	–	–	–	0.270	0.940	–	–	0.060
Cement Portland	–	–	1.610	0.057	0.047	0.019	–	0.950	0.109	0.09	0.050
Cement Hoogoven I	–	–	0.510	–	–	–	0.066	0.300	0.640	–	0.060
Blastfurnace slag cement	–	–	0.425	0.015	0.012	0.005	–	0.250	0.729	0.024	0.050
Portland ash cement	–	–	1.190	0.042	0.035	0.014	–	0.700	0.081	0.317	0.050
Cement CH	–	1.150	0.346	–	–	–	–	–	–	–	0.030
Cement N	–	1.640	–	–	–	–	–	–	–	–	0.050
Portland cement NL1	1.410	1.600	–	–	–	–	–	–	–	–	0.060
Cement S	–	1.360	–	–	0.046	0.009	–	–	–	–	0.046
Cement SF1	–	1.200	–	–	–	–	–	–	–	–	–
Cement SF2	–	1.550	–	–	–	–	–	–	–	–	–
Portland cement A	0.190	1.200	–	–	–	–	0.017	–	0.122	0.027	0.064
Portland cement NL2	1.071	–	1.045	0.028	0.066	0.019	0.047	–	0.095	0.076	0.050
Portland cement NL3	1.325	–	1.316	0.056	0.047	0.014	–	–	0.108	0.089	0.060
Blastfurnace slag cement NL1	0.532	–	0.287	0.007	0.017	0.005	0.025	–	0.700	0.020	0.050
Blastfurnace slag cement NL2	0.423	–	0.420	0.018	0.015	0.004	–	–	0.675	0.285	0.060
'Yleis' cement	–	0.066	–	–	–	0.004	–	0.822	0.067	–	0.053
'Rapid' cement	–	0.042	–	–	–	0.005	–	0.906	0.020	–	0.067
'Pika' cement	–	0.026	–	–	–	0.004	–	0.863	–	–	0.061
'Mega' cement	–	0.030	–	–	–	0.005	–	0.907	–	–	0.058
'SR' cement	–	0.020	–	–	–	0.005	–	0.834	–	–	0.043

Except for the last five Finnish cements, the order of magnitude of limestone and/or loam consumption is approximately 1.60 kg/kg cement for Type I cement, and logically less for other cement types. The reason for the Finnish anomaly is not clear, and it is probably an error. The other ingredients are used in similar quantities as for the other cements studied.

Because CO_2 emissions are primarily influenced by the quantity of limestone and its transformation during clinker production, this is the most important factor to be taken under consideration.

3.2. Energy consumption

The study of the energy consumption conforms to the method stated in ISO 14042:2000 [19]. It recommends using energy consumption as one of the key parameters for checking the reliability of inventories used in product or process LCAs. The total energy consumed is divided into thermal energy and electricity (as shown in Fig. 1). The latter only considers the amount of electrical energy used by plant operations within each cement factory. The origin of this energy source is the national grid which, for each country, is supplied by a unique combination of power plants (nuclear, hydroelectric, geothermal, solar, marine, wind, etc.).

The clinker kiln is the main consumer of thermal energy. Almost 90% of the total energy consumed by the system is due to the production of clinker and, thus, cements with lower clinker contents consume less energy. The distribution between electrical and thermal energy is factory dependent. For all the Type I cements, the average energy consumption is 4.31 MJ/kg cement (excluding the Finnish average which is for both Types I and II).

4. Output data analysis

The analysis considers the following four major emissions as the fundamental parameters in determining the reliability of the inventories:

- CO_2—due to its paramount influence on the greenhouse effect and induced climatic change on a global level.
- NOx—due to its contribution to acidification and eutrophication on a regional level.
- SO_2—due to its contribution to acidification on a regional level.
- Dust—due to its important visual and direct impact on the image and health of the environment and its habitants on a local scale.

The amount of each of the four emitted substances is theoretically determined by a commonly accepted numerical methodology [20]. These four principal emissions are determined separately for each of the main processes of cement production responsible for them.

The contribution to the emissions (in g/kg cement) by the combustion of each fuel type (burn of fossil fuels) used in the production of thermal energy is calculated using the emission or equivalency factors given by this model and the net calorific values of each fuel and /or their typical carbon emission factors.

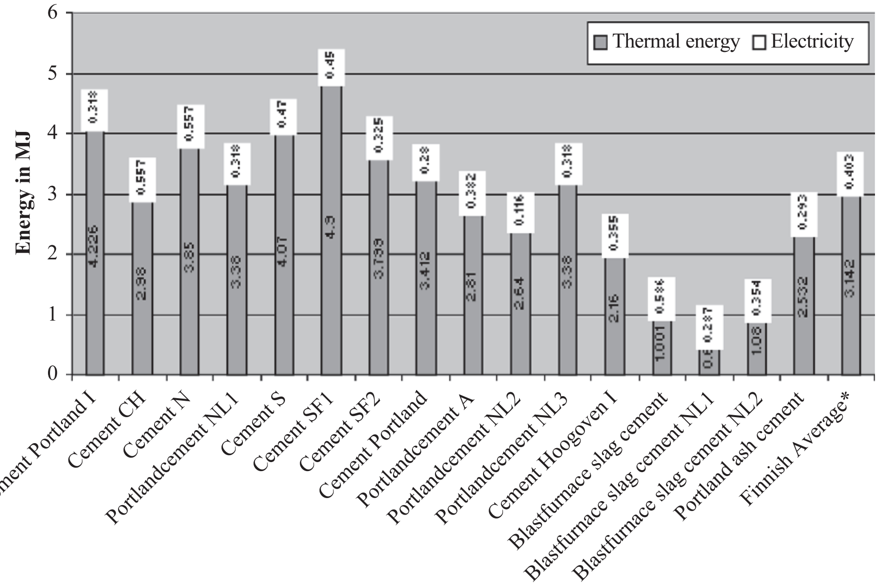

Fig. 1. Energy consumption (in MJ) for the production of 1 kg of cement (electricity and thermal energy). *Values correspond to Finland's two cement plants; they are thus representative of the national average.

Emission factors are also employed to estimate the CO_2 emissions due to chemical reactions occurring in the kiln (decarbonisation of clinker constituents). In the case of SO_2, the emissions originating from the kiln's chemical reactions (oxidisation of sulphur contained in the raw materials) are estimated according to a simplified approach based on average values obtained from research in the Nordic countries [20].

All the emissions derived from electrical energy consumption are determined considering the typical national emission values from power production (in g/MJ), together with the amounts of energy used by each production system.

The sum of these estimated emission levels for each of the cements (excluding the national average values) are then compared with the measured values specified in the inventories (given in Table 3). This adopted methodology allows for a feasible comparison of the reliability of the inventory data.

4.1. CO_2 emissions

The main CO_2 emissions are a result of the chemical reactions in the clinker kiln, the fuel combustion during clinker production and the energy consumed throughout the whole production process (clinker and cement). Other emission sources, such as fuel usage during material extraction or fuel usage in the distribution phases (e.g., internal transport within factory), are not considered because they are outside the system boundaries for each cement studied or have been considered negligible. On average, quarrying/mining and transportation/distribution represent only 1% and 3% of total energy consumption, respectively (within the limits from cradle to gate).

The amount of CO_2 emitted depends on the cement's clinker content and the values for the cements considered in this study are shown in Fig. 2. The CO_2 emission for cement Type I is approximately 800 g/kg cement, less for the other cement types with lower clinker contents. The national average emissions agree with the average for the individual Type I and II cements, hence, they can be assumed to represent the same (Fig. 2).

Table 3
Summary of the main substances emitted to air (in grams) by the production of 1 kg of cement as given by the inventories studied

Type	Original	Emissions to air (g)			
	Nomenclature	CO_2	NOx	SO_2	Dust
I	Cement Portland I	355.00	0.96	0.43	10.00
	Cement CH	810.00	2.00	0.60	0.30
	Cement N	813.00	2.09	0.67	0.18
	Portland cement NL1	853.00	2.58	0.09	7.50
	Cement S	805.00	1.94	0.45	0.16
	Cement SF1	780.00	3.70	0.63	0.39
	Cement SF2	812.70	2.95	1.33	0.32
II	Portland Cement	918.30	3.11	1.16	0.24
	Portland cement A	586.00	1.57	0.12	0.17
	Portland cement NL2	807.00	2.95	0.09	0.19
	Portland cement NL3	289.00	0.71	0.98	79.60
III	Blastfurnace slag cement	221.70	0.51	0.51	10.00
	Cement Hoogoven I	334.00	1.11	0.58	0.08
	Blastfurnace slag cement NL1	212.00	0.85	0.03	0.14
	Blastfurnace slag cement NL2	134.00	0.40	0.43	88.60
IV	Portland ash cement	692.90	2.33	0.90	0.18
I and II	Finnish average[a]	738.00	2.17	0.17	0.14
Varies	UK plant[b]	850.00	3.55	2.06	0.27
Varies	Danish average[c]	973.0	3.70	0.60	0.10

[a] Values correspond to Finland's two cement plants and thus represent national average.

[b] Average emissions from a typical UK Portland cement manufacturer [21].

[c] Values correspond to the only cement plant in Denmark [22], and thus represent national average.

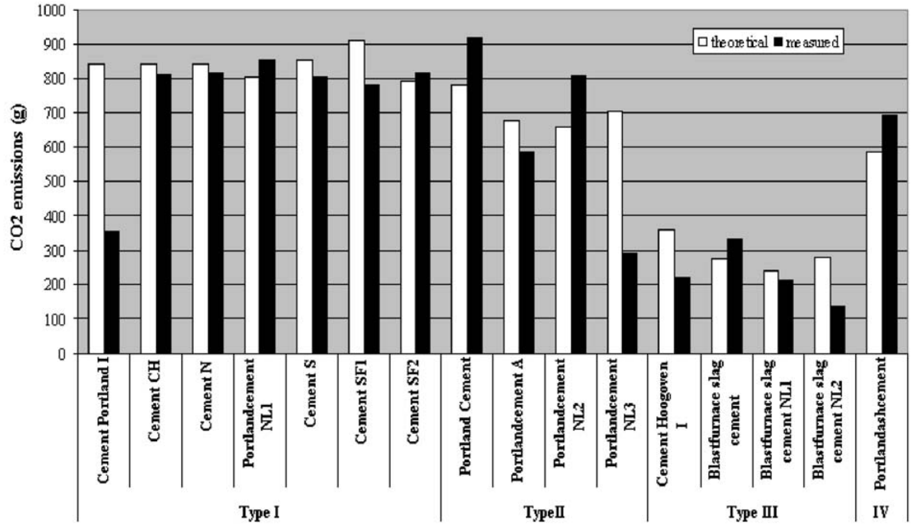

Fig. 2. Comparison of total CO_2 emissions according to the theoretical model and total given in the inventory for each cement type.

The notably lower CO_2 values (Cement Portland I and Portlandcement NL3) are probably due to numerical errors or a result of poor definition of the system boundaries. Portlandcement NL3 is an anomaly also because its data is treated in a unique manner and, possibly, some aspects related to clinker production have not been incorporated in its inventory.

Overall, the chemical reactions produced within the clinker kiln and the fuel used to heat it contribute to the majority of CO_2 emissions (more than 90% for cement types I). The proportion of the emissions attributable to other energy usage is much inferior to this (less than 10% for cement types I).

The general agreement of the values estimated theoretically and of those given in the inventories validates the use of the theoretical model as a comparative tool. Its use as such in inventory analyses is thus justifiable.

The reduction of CO_2 emissions for cement types III is logical, as clinker is substituted by up to 66% of the total by GGBFS or ashes. The use of these coproducts can significantly reduce the environmental burdens attributable to cement production.

The percentages of CO_2 emissions corresponding to the principal phases in cement production are 59% due to the chemical reactions during the production of clinker, 35% due to the total fuel consumption of each stage and 6% due to other energy consumed by the whole system.

From the data previously given, the reductions of CO_2 emissions allowed by the use of cements with lower clinker contents are evident. This reduction is directly linked to the amount of additions used and can be very important, even higher than the 50%, for cements with low clinker content. However, other parameters, as the mechanical strengths, can limit the reductions that can be reached in practical situations.

4.2. NOx emissions

The NOx values refer to both NO_2 and NO emitted to the air. These are mainly an output from fuel usage during clinker production and energy consumption throughout the entire process chain. The NOx emissions are not a result of the chemical reactions, but of the burning of fuel. The values thus depend on the types of fuel used and level of technology of the process (factors influencing combustion such as temperature, excess of air, etc.). If a combination of fuels is used, the corresponding NOx values (as determined using emission factors) are simply added to give the total.

Again, NOx values depend primarily on the clinker content of the cement; that is, the main sources of NOx are the processes required for clinker production. Cement types I average 2.4 g of NOx per kilogram of cement. Variations are greater than for CO_2, but the reasons for the discrepancies are the same. The same cements, generally, do not fit the trend, suggesting a consistent source of inaccuracy. The national average values agree with other cement types I and II, again implying that they represent these two cement types. Furthermore, the good data compatibility indicates that NOx amounts emitted by cement plants can be measured to an adequately high degree of accuracy (Fig. 3).

The contribution to the NOx output by the burning of fossil fuels used for the production of clinker is in the order of magnitude of 10 times more than that by the energy used in all the other phases of the production process. The agreement of theoretical and recorded NOx values proves that the method of numerical estimation may be used as an alternative to in situ measurement of emissions from each process step.

The most significant differences between measured and estimated values are due to the same reasons as for the other emissions. Incorrect interpretation of some data could also

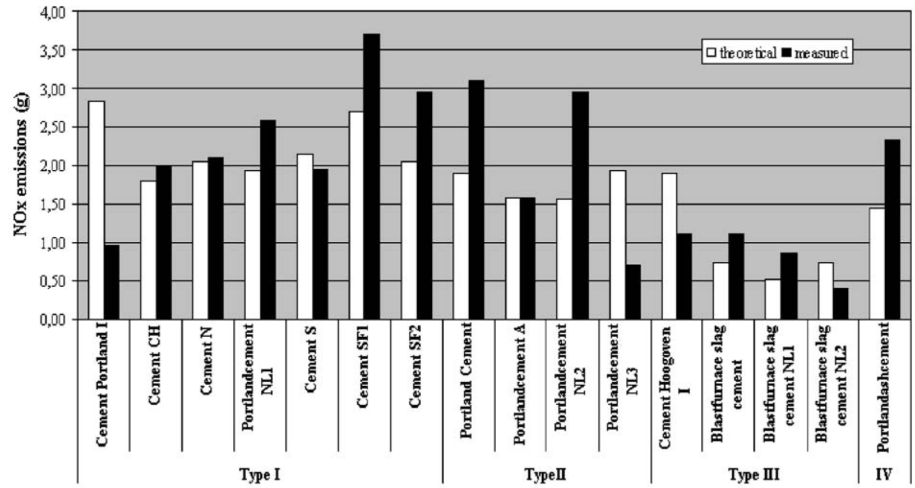

Fig. 3. Comparison of total NOx emissions according to the theoretical model and total given in the inventory for each cement type.

be the reason for values that are estimated lower than those given by the inventories (i.e., for cements SF1 and SF2, whose CO_2 emissions agreed well).

In general, a higher degree of clinker substitution (by GGBFS and ashes) reduces NOx emissions. Emissions derived from raw material extraction are outside the defined boundaries and are thus not included in the cement production. If they were to be included, the possible positive effects of using waste as raw material (e.g., as fuel) need to be taken into account.

4.3. SO_2 emissions

The primary contributors to SO_2 emissions are the chemical reactions in the clinker kiln (due to the sulphur content in the clay and other raw materials), the combustion of sulphur contained in the fossil fuels used in clinker production and the combustion of sulphur during the production of energy consumed by the whole process. The majority of SO_2 emitted, however, is derived from the fuel combustion and the processing of raw material in the kilns. Evaluation shows that some of this emission (around 70–95% of the fraction not attributable to energy production at the national power plants) is absorbed due to the alkalinity of clinker [20]. The excess is emitted to the atmosphere.

As for CO_2 and NOx, the SO_2 amount depends on the cement type, that is, the clinker content in the cement. The general results show a wider dispersion of data than for the other pollutants. Between 0.4 and 0.6 g of SO_2 emitted per kilogram of cement applies to all the Type I cements studied. This is less for lower levels of clinker utilisation. Variance above and below the average can be seen. The reasons for data discrepancy are as previously suggested (Fig. 4).

Average SO_2 emissions are estimated at 300 mg/kg cement produced when the sulphur content in the clays and other raw materials or the degree of absorption is not known [20]. This applies for all cements of Type I, from

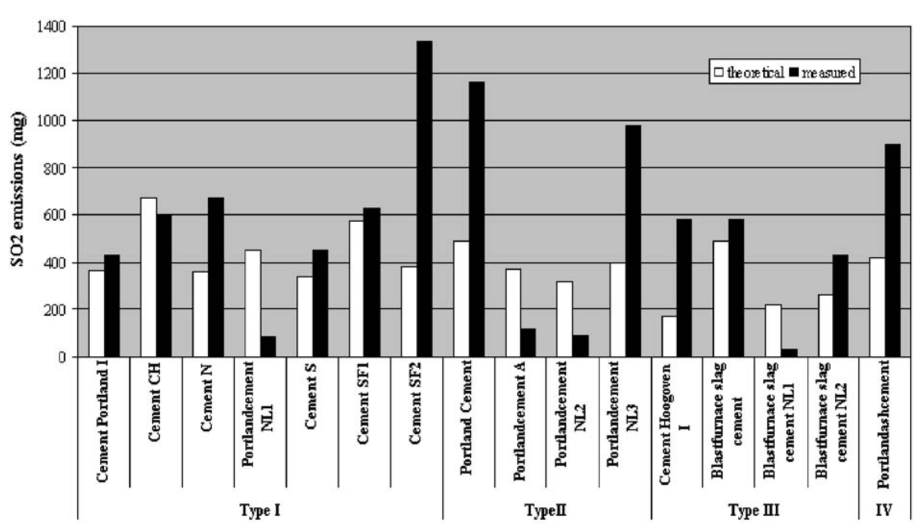

Fig. 4. Comparison of total SO_2 emissions according to the theoretical model and total given in the inventory for each cement type.

which the values for other cements have been extrapolated, knowing their clinker content.

The total estimated values given are the sum of the emissions from the oxidisation of sulphur contained in the fuel used for the clinker kiln and the raw materials treated in it plus the emissions derived from energy production (proportioned according to the amount of energy consumed by the entire clinker and cement production system).

The majority of the emissions, in general, above 40%, are due to the chemical reactions in the kiln. The oxidisation of sulphur contained in the fuels contributes the least, whilst the intermediate values are a result of the production of the energy consumed by the whole process.

The UK plant's SO_2 average is considerably higher than the rest. However, since the raw materials and fuels used across Europe can be supposed to have a similar composition, this value probably reflects the technology of production. Nordic countries and the Netherlands have, in general, a much higher use of alternative fuels; they have more advanced and efficient waste recycling schemes in place. The low Finnish average could be due to this same reason.

The comparison of SO_2 emissions obtained using the model and of those given in the cement inventories agree in some cases. Despite the significant anomalies, the numerical estimation method can sometimes be a feasible alternative to in situ measurements. Theoretical values are both below and above those given by the inventory. Many of these discrepancies are associated with the cements that have also shown poor comparative results in terms of the other emissions.

4.4. Dust emissions

The amount of dust emitted by the different cement production systems varies greatly. This is mainly attributable to the various levels of technology used. A general figure is about 0.2–0.3 g/kg cement. However, the maximum values are 79.6 and 88.6 g/kg cement for Portland cement NL3 and Blastfurnace slag cement NL2, respectively. Again, a different system boundary definition could be the reason for this including in some cases not only local (at the factory) emissions. The national average values agree with the individual cement figures.

The numerical estimation of dust levels takes into account only the amount of electrical energy and fossil fuels consumed in the cement production (a general method has not been developed). For this, it uses the typical dust emission (in g/MJ) from each country's power generation plants and the emissions corresponding to each type of fossil fuel used in the production of thermal energy. Due to a lack of parameters, the emissions from the mechanical actions of sand grinders, raw meal and cement grinding mills, etc. are not included for any of the cases analysed. This omits the most significant sources of dust emissions. Realistic dust levels are thus not considered.

Some of the cements have dust levels in excess of 0.5 g/kg cement. A comparative analysis is thus not very useful. A clear lack of homogeneous data consideration and treatment is evident for these cements. For the other cements, general data compatibility is evident between the estimated and recorded values. The calculation model is thus reliable and can serve as an alternative to other means of estimating dust emissions, originating from electricity production and the burning of fossil fuels. Means of measuring and estimating the most significant dust levels need to be developed and implemented.

5. Conclusions

- The system boundaries of the different cement production systems in the inventories are homogeneous, which makes their analysis difficult.
- The average values representing typical plants agree, in general, with individual cement data. Data for cement produced in less technologically advanced countries need to be collated so that more comprehensive comparisons can be achieved.
- The available theoretical models, based on average results, give reasonable emission levels and can thus serve as a reference to the measured values. They are a reasonable alternative to in situ measurements and monitoring (definitely a feasible option for CO_2 emissions). Since CO_2 is the most significant greenhouse gas (in terms of amount released and environmental impact), the use of theoretical estimation can minimise the need for in situ measurements.
- The emissions are primarily produced by clinker manufacture, both by the chemical reactions, as well as the combustion of fossil fuels that this requires.
- Lowest possible energy cements are achieved by using maximum amounts of clinker alternatives: GGBFS, fly ashes and other cementitious or pozzolanic materials. Environmental burdens are thus also reduced by such substitutions.
- Higher levels of technology and increased use of alternative fuels are key parameters for obtaining lower emission levels and decreasing the consumption of nonrenewable energy resources.

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