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Comparison of critical input parameters and key environmental indicators for cement production in India

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A B S T R A C T

The effective application of life cycle assessment (LCA) methodology for impact assessment relies on good input data quality and relevant characterisation factors that convert the inventory to appropriate impact indicators. Additionally, having representative data from relevant geographical locations and specific technologies is imperative for assessing national and regional impact contributions. Therefore, this study utilised a database generated for cement production in India, illustrating the approach to be used when no databases are available, as in developing economies. The specific energy consumed (kiln efficiency), type and amount of fuel, and electricity production are critical for clinker production. The identified parameters from different cement plants were compared along with the assessed key environmental indicators, such as the global warming potential and energy consumed. The range of impact indicators associated with clinker and cements were assessed for the typical Indian case. For ordinary portland cement (OPC), in the ground-to-gate system, the CO_2 emissions for a tonne of cement range from 910 to 1000 kg CO_2 eq., and energy consumed from 5440 to 6365 MJ, whereas the values for the gate-to-gate system vary from 840 to 905 kg CO_2 and from 3930 to 4580 MJ, respectively. The impact values of OPC are basically affected by the impact of the clinker and clinker ratio. The substantial lowering of the impacts in blended cements have been highlighted.

Keywords: *Cement production, Critical parameters, CO_2 emissions, Database of cement production, Energy consumed, Indian cement industry.*

1. Introduction

Constructed facilities are associated with a significant amount of greenhouse gas emissions and consequently have a major impact on climate change. Concrete is a widely used construction material with lower embodied carbon and energy compared to other materials [1]. Nevertheless, the impacts of cement production on global warming are significant due to direct CO_2 emissions from the limestone, and the use fuels as the major source of energy during clinkerization. There is, therefore, the need for calculating the environmental impacts of the clinker and cement produced for assessing the sustainability-related impacts and for facilitating improvements.

Life cycle assessment (LCA) is an effective tool for identifying environmental issues, and for calculating the impacts due to cement and concrete manufacturing processes. However, the reported values of the impact indicators from LCA for concrete and its constituents vary over a wide range. The reasons include the variations in the definition of the scope, functional unit, system boundaries and methodology of assessment, as well as the inadequate choice of characterisation factors, unreliable and uncertainty in the inventory data. Further, the life cycle inventory (LCI) and characterization factors used in most studies are based on global/national data averages or specific cases, which could lead to inappropriate estimations. India being the second largest cement producing country in the world, requires a properly established inventory data of cement production and characterization factors for reliable assessment of the impacts, which are of relevance locally and globally.

Primary (i.e., first-hand) data collected from the production are obviously more reliable and complete, requiring this to be done for specific geographic conditions and relatable technologies [2,3]. This is even more relevant for the Indian cases because of several technological and geographical differences with other markets, as stated elsewhere [3,4,5]. As the primary raw material used in the production of clinker or ordinary portland cement (OPC) is limestone, every integrated cement plant in India is located near a limestone quarry. The additional raw materials used (though minor in comparison with limestone) are marl, calcite, aragonite, shale, seashells, cement kiln dust, etc. Sand, fly ash, rice husk ash and slag can also be used (instead of clay). Obviously, there is a propensity to use locally available alternative materials, such as mudstone, pyrite cinder and red clay. The primary fuel is coal or pet coke, with the type and amount of alternative fuel varying based on the availability and cost. The amount of alternative raw materials and fuels used for cement manufacturing in India seems to be lower than the global average [5], and the clinker to cement ratio and the amount of electricity consumed per tonne of cement in India also vary significantly from global values [5]. Due to these differences and peculiarities, it is essential to have a specific database of clinker and cement production in India, and the same should be used for calculating the environmental impacts of concrete, concrete products or buildings components. Therefore, a specific data set was generated by collecting data for cement production from various plants in India and has been published to be used for LCA studies [6,7].

It is evident that reliable data is needed for meaningful LCA results, especially in terms of the inventory and characterisation factors. Further, the system boundaries should be clearly defined so that the interpretation is unambiguous. For plants in India, regional data needs to be collected and used, with relevant inventories and characterization factors [6], avoiding geographical and technological discrepancies. Such an approach could also be

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used elsewhere, especially in emerging economies, to calculate the environmental impact when the appropriate database is not available. Therefore, an 'ab initio' framework proposed to conduct LCA of cement and concrete systems to calculate climate change impacts (Global Warming Potential, GWP) and cumulative energy demand (CED) for cases where data is not readily available [6]. This is based essentially on the collection of inventory data from primary sources such as cement, aggregate and concrete plants. Priority is given, in the impact assessment, to primary conversion/characterisation factors obtained from Ultimate CHNS (Carbon Hydrogen Nitrogen Sulphate) or ultimate analysis and bomb calorimetry rather than default factors that vary with the methodology used. The quality of the ab initio framework has been assessed following the procedure of Junior et al. [8] and Weidema and Wesnaes [9], considering the data sources, type of data, geographical context, reliability and completeness, and found to be 'very good' [4, 6]. Data collected from different cement plants in India [7] will be analysed here and used to conduct LCA based on the ab initio framework to arrive at reliable ranges of embodied carbon and energy consumption associated with clinker and cement produced in India.

2. Methodology

The ab initio framework essentially follows the ISO guidelines [10,11] and complies very well with the quality requirements [8, 9], as explained elsewhere [3, 4, 6]. The goal of the present study is specifically to estimate the GWP (CO_2 emissions) and energy consumed for cement production in integrated cement plants and grinding units, with the typical processes. The functional unit considered is one tonne of the product, such as clinker, ordinary portland cement (OPC), portland slag cement (PSC), portland pozzolana cement (PPC) or ground granulated blast furnace slag (GGBS). The IPCC and cumulative energy demand single score indicator methods were used to calculate the climate change impacts (GWP, kg CO_2 eq.) and cumulative energy consumed (MJ) per functional unit considered. The primary data collected from six cement plants related to clinker, cement and electricity production are used along with the background and upstream processes from ecoinvent data base corresponding to India available was used as a part of inventory.

Three different system boundaries are considered for the environmental impact assessment of clinker and cement: (a) Ground-to-gate, (b) Gate-to-gate and (c) Cement Sustainability Initiative (CSI), each of which have been described in more detail elsewhere [3,4,12]. The ground-to-gate system is most complete, with the inclusion of all processes from the mines to the exit of the product(s) from the cement plant. In the gate-to-gate system, only those processes controlled by the cement plant are accounted for. Note that, in our approach, the extraction and transportation of limestone, and the transportation of materials (i.e., fuels and raw materials) by truck are also included in the gate-to-gate system. Such a modified system permits reliable comparisons with data compiled by industry sources and avoids assumptions that may be difficult to verify, such as extraction methods and shipping routes of fuels. However, it facilitates the assessment of the influence of decisions made for the mode of transportation based on cost by the cement plant. The CSI system, originally defined by the Cement Sustainability Initiative (CSI) Protocol, and presently being used for reporting by the Global Cement and Concrete Association (GCCA), only considers operations that can be influenced by the plant [13], similar to 'Scope 1 emissions' from company facilities as defined by IPCC [14]. This system, though not generally considered in the scientific literature, is of relevance due its extensive usage in the cement industry.

2.1 Inventory analysis through case studies

Data collected in India, during 2017-19, from four integrated cement plants, and two grinding units that procure clinker from elsewhere for the manufacturing of cement. The locations of the plants are given in Table 1, along with the corresponding products. The plants are distributed over the main cement-producing regions of India, corresponding to the country's limestone belts [15].

The average annual data for the collected from each plant by following an appropriate methodology can be found elsewhere [7]. Though the processes in the integrated cement plants studied here are similar, there are substantial differences in terms of type and amount of raw materials and fuels used, transportation distances, and the source and consumption of electricity. The similarities are mainly the following:

- All plants are located close to the limestone quarries.
- All the integrated plants had pre-heaters and pre-calciners, with systems for the utilization of heat from the exhausts.
- The fuel used is majorly pet coke, along with some coal and low amounts of alternative fuels.

Table 1 Plants considered in the study and the products manufactured

Case study notation	Location of cement plant (town, state)	Type of plant	Products of the plant
ND	Nandyal, Andhra Pradesh	Integrated cement plant	OPC, PSC, GGBS
NB	Nimbahera, Rajasthan	Integrated cement plant	OPC, PPC
MG	Mangrol, Rajasthan	Integrated cement plant	OPC, PPC
NM	Nimbol, Rajasthan	Integrated cement plant	OPC, PPC
AR	Arakkonam, Tamil Nadu	Grinding unit	OPC, PPC
TR	Toranagallu, Karnataka	Grinding unit	PSC, GGBS

The inventory dataset generated from the visits are accessible and is published in an open-source data repository [7] and are further discussed in the following sections.

2.1.1 Raw Materials

In all the cases, about 1550 kg of raw materials are used to obtain a tonne of clinker, with limestone being the predominant raw material (i.e., 84-91%), as is typical in most Indian cement plants. Consequently, the direct CO_2 emissions from limestone are similar (i.e., 520-550 kg CO_2 per tonne of clinker) among the different plants, as shown in Figure 1. Small quantities of pristine materials, such as bauxite, laterite and china clay, are used as the sources of iron, alkalis, silica, alumina etc. as per the requirements for the input feed. Importantly, several waste materials, such as flue dust, marble khanda (lumps), crushed slag and iron sludge, and zinc slag, are used in the raw meal, depending on their accessibility, to reduce limestone consumption (and cost). This scenario reflects the willingness of the cement producers to use waste materials, if technological and economic feasibility is ensured.

For the production of OPC, the clinker is ground with gypsum and filler material, mostly fly ash and limestone. The amount of the filler material (also known as performance enhancer) is about 6-7%. Sometimes, Granulated Blast Furnace slag (GBS) is also used to the cement, as seen in Appendix A of the data set published elsewhere [7]. Note that the gypsum used could be in the form of natural gypsum, anhydrite gypsum, phosphogypsum (denoted by some plants as chemical gypsum), jarosite and waste gypsum moulds. For PPC, the clinker is ground with fly ash (at 27% by weight in both Nimbahera and Mangrol) and for PSC, the OPC is blended with GGBS (at 47% by weight in Nandyal).

2.1.2 Fuels

The major source of energy for clinkerization in the Indian cement plants is through the burning of fossil fuels. It was observed, in the case studies, that the fuel required for the clinkerization varies from 92 kg (in Nimbol) to 120 kg per tonne of clinker (in Nimbahera), and specific energy consumption varies from 3160 (in Nandyal) to 3620 MJ/tonne (in Nimbahera). The primary fuels are pet coke and coal in all the plants, with mostly imported pet coke and coal being used in higher proportions than domestic coal, as can be observed in Figure 2. This is attributed to the lower calorific content and higher ash content of Indian coal [6]. The quantities of the fuels used, the carbon emissions and the thermal energy consumed for clinkerization are also shown in the same figure. The quantity of alternative fuels (AF) used, instead of primary fuel, varies among the plants, yielding thermal substitution rates of 4%, 8%, 2%, and 0% in the Nandyal, Mangrol, Nimbahera and Nimbol plants, respectively; note that the thermal substitution rate (TSR) is defined as the amount of thermal energy replaced by using AF to primary fuel consumption. Again, the plants are not averse to using wastes, as long as they are available near the plant, and imply no or significantly low treatment.

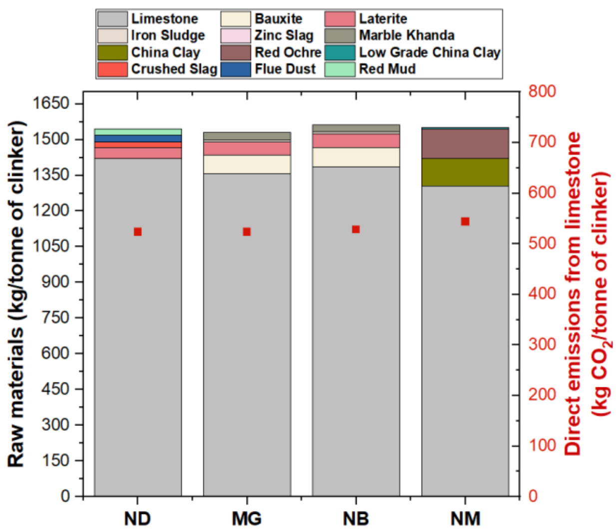

Figure 1 Comparison of types and amounts of raw materials used in clinker production

2.1.3 Electricity

Most of the electricity in a cement plant is consumed by raw meal preparation, kiln operation and cement milling; for example, in Nandyal, these processes consume 21.3 kWh/tonne of clinker, 25.6 kWh/tonne of clinker and 32.5 kWh/tonne of OPC, which together make up about 90% of the electricity needed for a tonne of OPC. Nevertheless, processes upstream of clinker production, such as limestone crushing, raw meal preparation and coal mill operations, also require substantial electricity. It is observed in Table 2, that the amount of electricity consumed to produce one tonne of clinker or cement is in the same range among three integrated plants, whereas it is significantly lower in Mangrol, which is a more modern plants than the others. The electricity for the milling is comparable to that of the two grinding units considered, i.e., Arakkonam and Toranagallu, as in Table 3. Note that OPC 43 Grade needs slightly less energy for grinding than that of OPC 53 Grade, as also is the case with PPC (though it has substantially less clinker content than OPC). It should also be noted that electricity consumed for grinding GBS to obtain GGBS is significantly higher than that needed to grind clinker, as the slag is much harder. The overall values of electricity consumption in the different integrated plants can be computed to give the data shown in Table 3. As indicated earlier, the electricity consumption at Mangrol is consistently lower for all products, while those of the other three integrated plants are similar. The electricity required for the PPC and PSC production is generally lower than that of OPC as seen in Table 4.

Table 2 Electricity used in clinker and OPC production

Plants / Processes		ND	MG	NB	NM
Production of 1 tonne of clinker (kWh)		52.2	47.4	56.7	51.3
For 1 tonne of cement (kWh)	Milling	32.5	29.4	36.0	31.4
	Packing	1.43	1.62	Not available	1.31
	Services	4.6	2.28		8.7

Table 3 Amount of electricity used in the plants for milling and packing

Categories	Grinding/Packing (kWh/tonne)					
	TR	AR	ND	MG	NB	NM
Grinding - OPC, 53 grade	30.0	33.5	32.5	29.4	36.0	31.4
Grinding - OPC, 43 grade					30.5	
Grinding – PPC (clinker with fly ash)		31.5				
Grinding – GGBS	36.7		41.1			
Blending – PSC (OPC with GGBS)	2.13		1.27			
Packing and Services	3.0	N.A.	6.0	3.9	4.0	10.0

Table 4 Total electricity consumption for the different products of the plants (kWh per tonne)

Plants / Products	ND	MG	NB	NM
Clinker	52.2	47.4	56.7	51.3
OPC 53 Grade	88.7	75.5	89.6	88.2
OPC 43 Grade			84.1	
PPC		56.1	67.6	70.9
PSC	68.9			
GGBS	41.1			

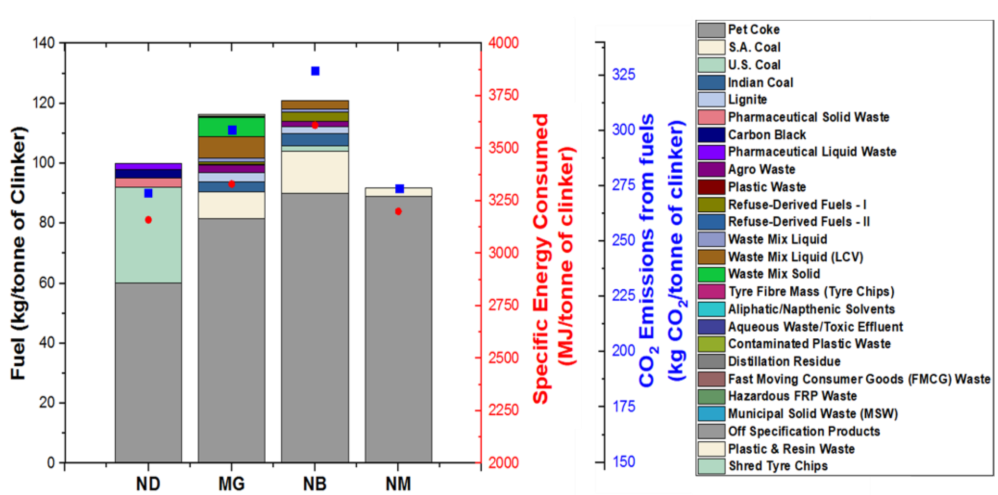

Figure 2 Comparison of types and amounts of fuel used in the clinkerization

3. Impact assessment

If we consider data from India [16], the emissions from cement manufacturing have been reported to be 46857 Gg of CO_2, 0.895 Gg of CH_4 and 0.544 Gg of N_2O in 2014. As carbon emissions dominate the environment impact, the emphasis in this work is on this particular indicator, as in other previous works [17]. In addition, the energy demand or the embodied energy is also considered as an important impact indicator [18]. These two parameters are linked closely to many of the 17 Sustainable Development Goals (SDGs) set by the United Nations. In relation to the construction sector, such goals include [19, 20]: Goal 7 - pertaining to conservation of energy and use of fossil fuels; Goal 9 - related to building more resilient structures; Goal 11 - related to performance and durability of the structures; Goal 12 - limited consumption and use of resources; and Goal 13 - related to the reduction of the carbon footprint of cement and concrete.

The inventory collected from the cement plants are translated to impacts with the help of characterization factors that are case and input specific. Suitable factors are obtained following the hierarchy given by Gettu et al. [5], and Basavaraj and Gettu [6], ranging from reliable test data down to factors in global guidelines. The characterization factors specific to each case and source are given in Appendix A of the published data set [7].

The unit to represent CO_2 emissions considered is either kg CO_2 eq. or kg CO_2, as appropriate. CO_2 eq. used in the ground-to-gate system includes the equivalent emissions (CH_4, N_2O etc.) from upstream processes, such as extraction of fuel, transportation, and electricity production, for which characterization factors have been taken from the ecoinvent database [21]. However, in the gate-to-gate system, processes such as extraction of fuel, and default upstream processes for transportation and electricity are not considered, and only direct emissions are calculated. Consequently, the unit is CO_2, and not CO_2 eq. Nevertheless, in the case of cement production, the emissions of other gases responsible for GWP are significantly low compared to that of CO_2 to make a significant change in the values obtained [16, 17].

3.1 Impacts due to electricity used in cement plants.

In India, most cement plants have dedicated captive power plants (CPPs) to produce the electricity needed while only a few depend on the grid. The majority of the power produced in the CPP is used by the plant, with the surplus sometimes being fed into the grid. The impacts due to electricity production differ between the coal-fired thermal power plants (TPPs) on the grid and CPPs due to the thermal efficiency, type and amount of fuel, losses, etc., with the TPPs generally being more efficient than CPPs. Evidently, the electricity procured from the grid is a combination of that produced using non-renewable resources, such as coal, natural gas, oil in thermal power plants (TPPs), and renewable sources, such as hydroelectric power plants, windmills, and nuclear and solar power plants. The losses due to transmission in case of grid electricity are to be included to obtain the impacts associated the grid electricity used in the cement production processes.

In order to calculate the impacts of the electricity generated at the plants, data (i.e., annual average) was collected from the CPPs of three integrated cement plants; the plant at Nandyal used grid power, as in the case of the Toranagallu grinding unit, while the Arakkonam grinding unit had a generator fuelled by heavy furnace oil. The primary processes relevant to a CPP in terms of impacts are the extraction and transportation of coal, and the burning of coal (leading to direct emissions); the coal used as the fuel is usually the same as that in the clinker production. The impacts related to the infrastructure of the CPP have not been considered in the present analysis as they are estimated to be very small. Similarly, the losses due to the transmission of electricity within the cement plant are ignored as they are considered to be relatively low. Data from the Energy Statistics Report (2020) [22, 23] was used to calculate the average impacts due to electricity taken from the Indian grid, for the financial year 2017-18, considering the split-up of electricity from renewable and non-renewable sources. The data collected, characterization factors used, and the corresponding impacts calculated for the electricity produced in the CPPs and a typical Thermal Power Plant (TPP) of the National Grid are given in the Appendix B of the published data set [7] and the Supplementary material of this paper (Annex 1), respectively.

Comparing the three CPPs assessed, it is found that the amount of coal consumed for 1 kWh of electricity in Nimbol (NM) is 0.515 kg whereas in the cases of CPP of Mangrol (MG) and Nimbahera (NB) plant, it was 0.58 and 0.89 kg, respectively. The higher values for Nimbahera are primarily due to differences in the type of fuel used as well as the lower efficiency of the plant. The imported coal has higher calorific content than Indian coal, though the carbon emissions are also higher, and the ash content is lower. For reference, the Mettur TPP that is connected to the grid (see Appendix B of the published data set, Table 1 [7]), uses mostly Indian coal, and the corresponding consumption is 0.72 kg/kWh. The LCA framework has been used to calculate the impacts associated with electricity production. The impact associated with electricity produced in cement plants and India grid (general) are given in Table 5, which are used as the characterisation factors for electricity used in cement plants.

The impacts associated with the electricity used in different plants varies from 72-134 kg CO_2 eq. and 880-1267 MJ per tonne of clinker, 122-211 kg CO_2 eq. and 1400-2000 MJ per tonne of 53 grade OPC and 100-160 kg CO_2 eq. and 1040-1510 MJ per tonne of PPC in case of ground-to-gate systems. Whereas, in gate-to-gate system the impacts are in the range of 49-97 kg CO_2 and 461-857 MJ per tonne of clinker, 82-153 kg CO_2 and 1000-1354 MJ per tonne of 53 grade OPC and 77-116 kg CO_2 and 741-1021 MJ per tonne of PPC. These values are compared and given in Table 6.

Table 5 Characterization factors for electricity produced in CPPs and the grid

Plant	Ground-to-gate		Gate-to-gate	
	Emissions kg CO_2/kWh	Embodied Energy MJ/kWh	Emissions kg CO_2/kWh	Embodied Energy MJ/kWh
NB	2.36	22.34	1.71	15.11
MG	1.82	18.56	1.37	13.20
NM	1.81	18.65	1.34	13.43
Indian Grid#	1.38*	19.50*	0.93	8.83

*Ground-to-Consumer, from ecoinvent database.
#Values include losses during transmission

Table 6 Impacts due to the electricity consumption at different plants

Ground-to-Gate								
Product	**CO_2 Emissions, kg CO_2 eq.**				**Energy Consumed, MJ**			
	ND	MG	NB	NM	ND	MG	NB	NM
Clinker	72	86	134	93	1018	880	1267	957
OPC 53 Grade	122	137	211	160	1729	1401	2002	1645
OPC 43 Grade			198				1879	
PPC		102	160	128		1041	1510	1322
PSC	95				1344			
GGBS	57				801			
Gate-to-Gate								
Product	**CO_2 Emissions, kg CO_2**				**Energy Consumed, MJ**			
	ND	MG	NB	NM	ND	MG	NB	NM
Clinker	49	65	97	69	461	626	857	689
OPC 53 Grade	82	103	153	118	783	997	1354	1185
OPC 43 Grade			144				1271	
PPC		77	116	95		741	1021	952
PSC	64				608			
GGBS	38				363			

All the values are reported per tonne of specific products.

3.2 Impacts due to transportation of the raw materials and fuels

The transportation process is common to all the processes involving raw materials sourced from different places. The consequent impacts depend on the amount of materials, transportation mode and the distance of transportation. The inventory parameter and the impacts for transportation are expressed in terms of a tonne-kilometre (t-km). The impacts calculated for the default processes from SimaPro with the ecoinvent database are given in Table 7. These have been used as the characterisation factors in the ground-to-gate systems of the cement production for the transportation processes. The impacts for rail transportation from default impact assessment modelling using ecoinvent dataset in SimaPro was found to be similar to those given by Hill et al. [24] and Van Essen et al. [25].

In the gate-to-gate system, only the diesel consumed during truck transportation is included in the inventory and impact calculation. For this purpose, a sample on-site survey was conducted with the drivers involved in transporting materials (i.e., fuel, alternative fuels, and raw materials) for estimating the diesel consumption per km. Accordingly, the average consumption in a truck with a capacity of 23 MT was found to be 3 kilometres per litre for a fully loaded truck and 4 km per litre when it is empty. The conversion factors for diesel were taken from data given by a cement plant as 0.07 kg-CO_2/MJ and 42.68 MJ/kg with a density of 0.84 kg/litre, which are similar to those given by IPCC. The consequent impacts for the gate-to-gate system are given in Table 8 are considered as the characterization factors for the impact calculations. Further details about the transportation processes are given in the Supplementary Material of this paper (Annex 2).

Table 7 Impacts considered for the transportation of raw materials, in the ground-to-gate system.

Transportation mode	CO_2 emissions (kg CO_2 eq./t-km)	Energy consumed. (MJ/t-km)
Train (Freight)	0.0467	0.77
Truck, with 22 MT capacity	0.0920	1.690
Ship	0.0192	0.0113

Table 8 Impacts considered for transporting the raw materials in the gate-to-gate system.

Transportation mode	CO_2 emissions (kg CO_2/t-km)	Energy consumed. (MJ/t-km)
Truck (full)	0.0385	0.5195

3.3 Impacts of Clinker Production

Considering the data collected from the Nandyal plant, the carbon emissions and energy consumed for 1 tonne of clinker have been calculated for the three systems discussed earlier, and the results are shown, respectively, in Figure 3 and 4. The corresponding characterization factors used are those specified in the Appendix C of the published data set [7]. It can be observed, as expected, that the CO_2 emissions for the gate-to-gate system (i.e., 850 kg) lie between the other two values, each separated by about 10%. In all cases, the emissions are dominated by those due to the conversion of limestone and the combustion of fossil fuels. The variation in the embodied energy, from 3730 MJ for the gate-to-gate system, however, is more dramatic due to the influence of the extraction, processing and transportation of fossil fuels used for clinkerization, as well as that of the generation of electricity. This highlights the significance of the clear definition and recognition of the system used for such calculations. Similar analyses have been done for all the integrated plants considered, and the results can be found in Appendix C of the published data set [7].

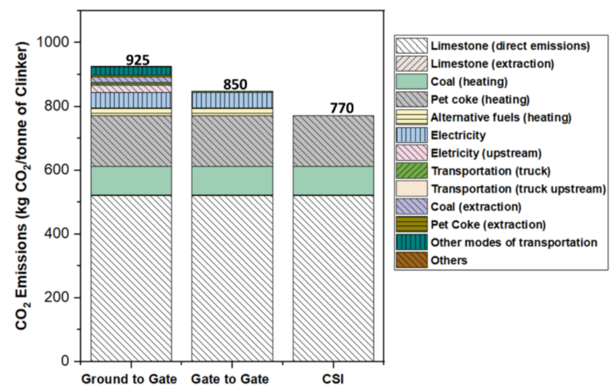

Figure 3 CO_2 emissions per tonne of clinker for the different systems

The values of the CO_2 emissions and energy consumed for clinker production at the different cement plants for both the ground-to-gate and gate-to-gate systems, are shown in Figure 5 and 6, respectively. The CO_2 emissions per tonne of clinker for the gate-to-gate system range from 845 to 950 kg CO_2, whereas in the ground to gate system, they range from 945 to 1030 kg CO_2. Similarly, the energy consumed varies from 5240 to 6120 MJ in the ground-to-gate system while the range is 3730 to 4535 MJ in the gate-to-gate system. The energy and emissions are least in Nandyal and highest in Nimbahera as latter is less efficient, being an older plant, as already reflected by the high specific energy consumption during clinkerization at Nimbahera (see Figure 2). The higher energy requirement leads to more fuel usage and corresponding emissions, despite the direct CO_2 emissions from limestone conversion being similar.

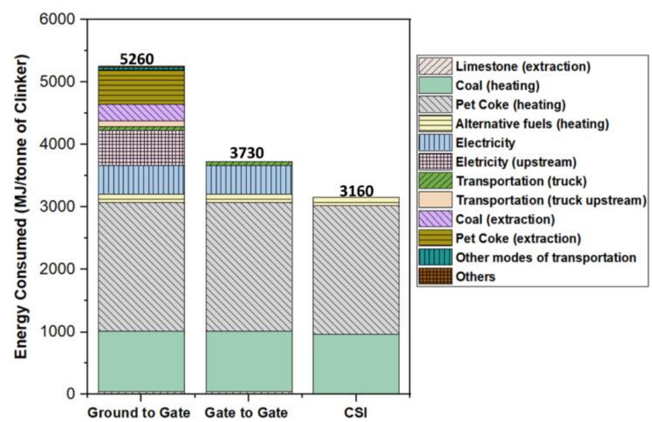

Figure 4 Energy consumed per tonne of clinker for the different systems

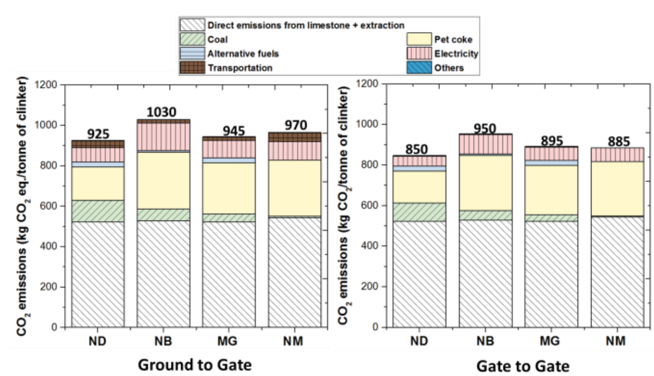

Figure 5 CO_2 emissions in the different case studies

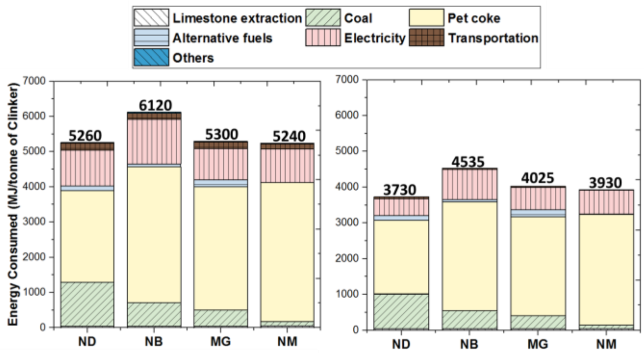

Figure 6 Energy consumed in the different case studies

In all the cases, the highest contributor to CO_2 emissions is the limestone, followed by the burning of fossil fuels and then the electricity production. The direct emissions from the limestone are quite similar, varying over a narrow range of 515 to 525 kg CO_2 /tonne of clinker, depending on the $CaCO_3$ and $MgCO_3$ content; they are responsible for 50%-65% of the CO_2 emissions depending upon the system considered. The emissions from the other raw materials only arise from their transportation, with no direct emissions. It is evident that the reduction of direct emissions is only possible when the limestone is replaced substantially by alternative decarbonized materials.

In the ground-to-gate system, the overall CO_2 emissions range from 925 to 1030 kg CO_2 eq./tonne of clinker, with the least being that of Nandyal and the highest in Nimbahera. The range of unit energy consumed is 5270-6120 MJ, with the least being the cases of Nimbol and Nandyal whereas the highest is in Nimbahera. The processes that make the difference are the extraction and transportation of fuels used for clinkerization and electricity production.

The emissions and energy from fuels are highest in Nimbahera because of the large thermal heat requirement. Since the efficiency of the kiln is better in Nandyal, the thermal energy requirement is low, which in turn decreases the total energy consumed (as seen in the gate-to-gate system, which is majorly dependent on the specific energy consumed). The emissions from the fuels are seen to be responsible for about 30-40% of the total emissions, with an important influence of the type and amount of fuel. Considering the Nimbol and Nandyal plants, which have similar specific energy consumption and direct CO_2 emissions from fuel, it is seen that the overall CO_2 emissions in the former are slightly higher due to differences in upstream processes, such as electricity production and mode of transportation. The Nandyal plant uses grid electricity, and consequently CO_2 emissions due to electricity usage are lower despite using more electricity per tonne of clinker than the Nimbol plant.

The CO_2 emissions/kg of clinker are slightly higher than the values reported earlier by Prakasan et al. [26] for two cement plants in Ariyalur, Tamil Nadu, for the gate-to-gate system, since the transportation process was excluded by them. Further, the emissions obtained here are seen to be significantly higher than those reported from China [27, 28]. In the ground-to-gate system, the impacts obtained in this study are similar to the ranges reported from Spain [29,30] and Italy [31] but higher than those reported from Germany [32] and UK [33].

3.4 Impacts of OPC production

OPC production involves the grinding of clinker along with gypsum and performance enhances, followed by the processes of packing. The impacts of OPC are mainly governed by the clinker ratio (relative amount of clinker in the cement, by weight) and the impacts of the clinker production. The influence of these two factors is evident on the variation of CO_2 emissions and energy consumed among the case studies, as seen in Figure 7 and 8 for the ground-to-gate and gate-to-gate systems. The benefit of a lower clinker ratio in OPC is clearly visible in the ground-to-gate system for Mangrol (having a clinker ratio of 0.89), which has the least impacts. However, using clinker with lower impacts could be more significant, as can be seen in the case of Nimbahera where the overall emissions are highest in spite having the least clinker ratio (0.87). The energy consumption is least in Nandyal, though it has the highest clinker ratio, because of the low impacts associated with clinker production.

The impacts of grinding process in the production of OPC, which is mainly dependent on electricity, are relatively small; the impacts are about 2.6% and 7.2% for OPC produced in Nandyal, for the gate-to-gate system, in terms of the CO_2 emissions and energy consumed, respectively. The values are similar in the two grinding units, i.e., Arakkonam and Toranagallu; further details can be seen in Appendix C of the published data set [7], as the electricity consumption is similar. As expected, the impacts of OPC produced in a grinding unit are generally higher due to the transportation of the clinker. For example, the OPC of the Toranagallu plant uses the clinker from the Nandyal plant, which is about 250 km away by truck, resulting in higher energy consumption by the former but with only slightly higher overall emissions.

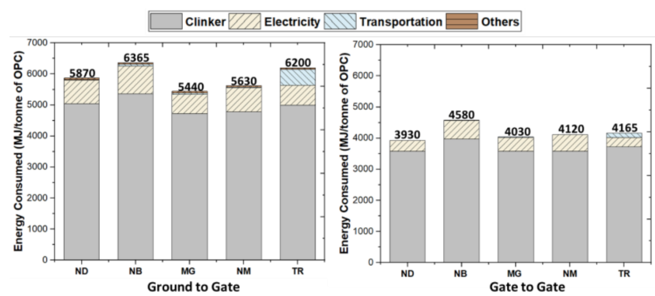

Figure 7 Energy consumed for OPC in the different cases

The CO_2 emissions/kg of OPC are slightly higher than the values reported earlier by Prakasan et al. [26] for two cement plants in Ariyalur, Tamil Nadu, for the gate-to-gate system, since the transportation process had been excluded by them. Further, the emissions obtained here are significantly higher than those reported from China [27,28]. In the ground-to-gate system, the impacts obtained in this study are similar to the ranges reported from Italy [31], higher than those reported from Spain [30], Germany [34], Australia [35], France [36], Portugal [37], Cuba [38] and lower than that reported from Myanmar [2].

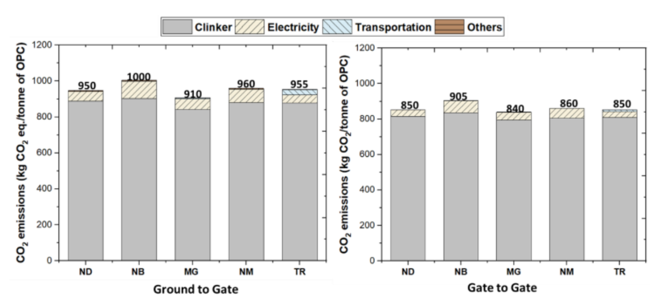

Figure 8 CO_2 emissions for OPC in the different cases

3.5 Production of PSC

The production of portland slag cement (PSC) involves the blending OPC or ground clinker and gypsum mixture with ground granulated blast furnace slag (GGBS), followed the packing processes; see Appendix C of the published data set [7]. In most cases, granulated blast furnace slag (GBS) is procured from a steel plant and ground at the cement plant to get the GGBS for blending, as in the Nandyal and Toranagallu plants that procure GBS from a steel plant in Toranagallu.

In case of GGBS production, electricity consumption for grinding contributes to most of the CO_2 emissions and energy requirement, followed by that of coal used for producing hot gases to drive off moisture from GBS before grinding. Note that in the case of GGBS produced in the Nandyal cement plant (Case study 1), waste hot gases from the kiln were used to dry the GBS, lowering the impacts of GGBS, as can be seen in Appendix C of the published data set [7]. The impacts of the GGBS produced in

Toranagallu is about 70 kg CO_2 eq. and 1080 MJ per tonne, and 60 kg CO_2 and 600 MJ per tonne, for the ground-to-gate and gate-to-gate systems, respectively. The production of GGBS could result in higher impacts if the impacts from the production of iron and steel are allocated to GBS, as opposed to being taken as zero as done here. The overall impacts associated with PSC are summarised in Table 9. It is seen that the impacts for the PSC produced in Toranagallu are lower than that from Nandyal since the GGBS content is about 60% of the PSC in the former while it is only 47% in the latter. It is evident that the higher clinker substitution leads to major reduction in the impacts in spite of the GGBS itself having a slightly impact in the former case.

Table 9 Impacts of PSC production

Impacts	**CO_2 emissions**	**Energy consumed**
Case study	Ground-to-gate	
	kg CO_2 eq./tonne	MJ/tonne
Nandyal	540	3670
Toranagallu	460	3560
	Gate-to-gate	
	kg CO_2 /tonne	MJ/tonne
Nandyal	475	2295
Toranagallu	395	2135

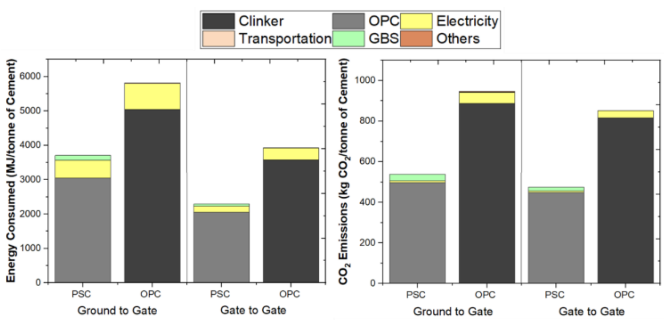

Figure 9 Comparison of the impacts of OPC and PSC produced in Nandyal

The effect of the substitution of clinker with GGBS is further emphasized by considering OPC and PSC produced in the same plant (Nandyal), as seen in Figure 9 for both gate-to-gate and ground-to-gate systems. The composition of the PSC is 53% (clinker 48% +gypsum 5%) of OPC and 47% of GGBS whereas the OPC has 95% clinker and 5% gypsum. It is observed that the PSC has about 43% and 37-40% lower carbon footprint and energy consumed, respectively.

3.6 Production of PPC

The production of portland pozzolana cement (PPC) involves the intergrinding clinker, fly ash and gypsum, followed the packing processes; see Appendix C of the published data set [7]. The fly ash used, normally conforming to ASTM Class F, is transported from nearby thermal power plants. The impacts of PPC produced in the Mangrol, Nimbahera and Nimbol plants differ slightly mainly due to the impacts of the clinker used since the clinker ratios are similar (about 65-68%). The values computed for the impacts are presented in Table 10.

As in the case of PSC, the benefit of the substitution of clinker by fly ash in PPC can be illustrated by comparing the impacts of OPC and PPC produced in Mangrol plant (see Appendices A and C, of the published data set, for details [7]. For a tonne of PPC, 650 kg of clinker is ground with ash (283.9 kg), gypsum (63 kg) and jarosite (3.1 kg), where the ash is a combination of 196.1 kg dry fly ash from and 58.2 pond ash from Kota (Rajasthan), along with 6.5 kg bed ash and 23.1 kg of internal bound transfer (IBT) fly ash from the CPP of the same plant. Note that the ash used did not undergo any secondary treatment (i.e., removal of moisture or grinding). It is seen that the PPC has about 27% and 24% lower carbon footprint and energy consumed, respectively, compared to OPC from the same plant, mainly due to the lower clinker content and electricity requirement. The impact of the transportation of the ash from Kota by truck accounts for 3-5% of the energy embodied in the PPC.

Table 10 Impacts of PPC production

Impacts	**CO_2 emissions**	**Energy consumed**
Case study	**Ground-to-gate**	
	kg CO_2 eq./tonne	MJ/tonne
Nimbahera	760	4920
Mangrol	670	4130
Nimbol	740	4515
	Gate-to-gate	
	kg CO_2 /tonne	MJ/tonne
Nimbahera	680	3470
Mangrol	620	3000
Nimbol	655	3210

Though the impacts of PPC are significantly lower than those of OPC, the lower clinker content of PSC results more substantial benefits. This can be illustrated by comparing the OPC and PPC produced in Mangrol with PSC produced in Nandyal by blending OPC and GGBS; see Figure 10.

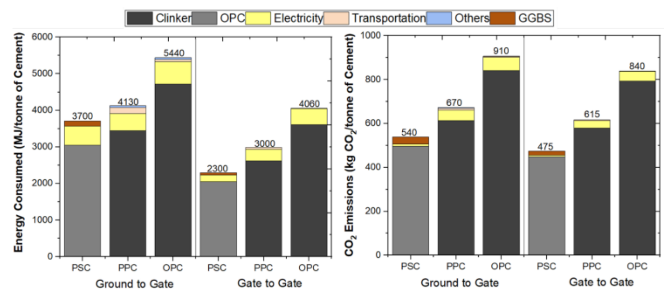

Figure 10 Comparison of impacts: OPC, PPC and PSC

4. Discussion and Conclusions

An ab initio framework has been used to conduct the life-cycle assessment (LCA) of clinker and cement for several Indian cases, where databases are not readily available. The data that is generated from the case studies can be used as the Indian specific database, and expanded further along the same lines, and employed for calculating the impacts associated with concrete systems and buildings/constructed facilities. Further, the impacts calculated could serve as benchmarks for assessing the influence of different types of raw materials, primary fuels and alternative fuels used in cement.

The primary data was collected from six cement plants in India, which included four integrated and two grinding plants. The impacts calculated per tonne of clinker, i.e., CO_2 emissions and energy consumed, varied among the cases and systems considered. For the ground-to-gate system (which includes all the upstream processes), the CO_2 emissions for a tonne of clinker range from 945 to 1030 kg CO_2 eq., and energy consumed from 5270 to 6120 MJ, whereas the values for the gate-to-gate system vary from 845 to 950 kg CO_2 and from 3730 to 4535 MJ, respectively. The parameters that govern the impacts are the direct CO_2 from limestone, specific energy consumed, type and amount of fuel used, and electricity source. The variations in the impacts among the cases are mainly due to differences in the efficiency of the kiln systems (SEC), type of fuel and amount of electricity used.

For OPC, in the ground-to-gate system, the CO_2 emissions for a tonne of cement range from 910 to 1000 kg CO_2 eq., and energy consumed from 5440 to 6365 MJ, whereas the values for the gate-to-gate system vary from 840 to 905 kg CO_2 and from 3930 to 4580 MJ, respectively. The impact values of OPC are basically affected by the impact of the clinker and clinker ratio. The transportation of clinker from an integrated unit didn't not have much influence on the impacts and further reduction could be possible if transported by train instead of truck.

In case of PSC (with data from two plants), the impacts associated are 460-540 kg CO_2 eq. and 3560 -3670 MJ, and 395-475 kg CO_2 and 2135-2295 MJ per tonne in the ground-to-gate and gate-to-gate systems respectively. For PPC, the impacts at three different plants ranged as 670-760 kg CO_2 eq. and 4130-4920 MJ, and 620-680 kg CO_2 and 3000-3470 MJ per tonne in the ground to gate and gate-to-gate systems, respectively. Consequently, it can be estimated that blended cements with about 28% and 47% of fly ash or GGBS, respectively, embody about 28-40% less carbon emissions and energy consumed compared to OPC in the Indian scenario.

The other parameters such as source and amount electricity could have a major influence on the impacts associated with cement production. These parameters which are identified to be critical could be majorly addressed in future to further reduce the CO_2 emissions and energy consumption during cement production.

Data Availability Statement

The data used in the study has already been published [7] and contains four appendices with information of relevance to the calculations made in this work. Appendix A provides the detailed inventories and characterisation factors used for all the case studies; Appendix B contains the detailed inventory, corresponding characterisation factors and impact values for electricity production in the captive power plants and the grid; and Appendix C gives the impact assessment results of all the products relevant for different case studies and for the three different systems considered for the LCA. Rest of the data related to impacts associated with transportation process and the electricity produced in the Indian grid is given in the Supplementary Material of this paper (Annex 1 and Annex 2)

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Authorship statement (CRediT)

Anusha S. Basavaraj: Data curation, Investigation, Validation, Conceptualization, Software, Formal analysis, Visualization, Writing original draft, Review and editing.

Ravindra Gettu: Conceptualization, Resources, Supervision, Project administration, Funding acquisition, Writing – review and editing

Declaration of competing interest

The authors declare no conflict of interest.

References

[1]. Scrivener, K. L. (2014). Options for the future of cement. Indian Concrete Journal, 88(7), 11-21.

[2]. Thwe, E., Khatiwada, D., and Gasparatos, A. (2021).“Life cycle assessment of a cement plant in Naypyitaw, Myanmar”, Cleaner Environmental Systems, Vol. 2, 100007.

[3]. Gettu, R., Patel, A., Rathi, V., Prakasan, S., Basavaraj, A.S., Palaniappan, S. and Maity, S. (2019). “Influence of supplementary cementitious materials on the sustainability parameters of cements and concretes in the Indian context”. Materials and Structures, 52(1), 10.

[4]. Basavaraj, A.S. and Gettu, R. (2022) “Life cycle assessment as a tool in sustainability assessment of concrete systems: why and how?”, The Indian Concrete Journal, Vol. 96, No. 4, pp. 1-20.

[5]. Cement Sustainability Initiative (CSI) (2013). “Technology roadmap: Low-carbon technology for the Indian cement industry. World business council for sustainable development and international energy agency.

[6]. Basavaraj A. S. (2022). “Assessment of sustainability parameters of concrete systems”, Doctoral Thesis, IIT Madras, India

[7]. Basavaraj, A. S. and Gettu, R. (2024). Primary life cycle inventory data for cement production, with relevance to sustainability assessment–Indian cases. Data in Brief, 54, 110258.

[8]. Junior, D. J. D. B., de Oliveira Gomes, J., and Bork, C. A.S. (2014). “Reliability of the sustainability assessment”, Procedia CIRP, 15, pp. 361-366.

[9]. Weidema, B., and Wesnaes, M. (1996). “Data quality management for life cycle inventories – an example of using data quality indicators”. Journal of Cleaner Production, Vol. 4, No. 3-4, pp. 167-174

[10]. IS/ISO 14040:2006. “Environmental Management – Life Cycle Assessment – Principles and Framework”, BIS, New Delhi, India.

[11]. IS 14044 (2006). IS/ISO 14044:2006. “Environmental Management – Life Cycle Assessment – Requirements and Guidelines”, BIS, New Delhi, India.

[12]. Gettu, R., Patel, A., Rathi, V., Prakasan, S., Basavaraj, A.S. and Maity, S. (2016b). “Sustainability Assessment of Cements and Concretes in the Indian Context: Influence of Supplementary Cementitious Materials”, Proc. Fourth Intnl. Conf. on Sustainable Construction Materials and Technologies (Las Vegas, USA), Eds. N. Ghafoori, P. Claisse, E. Ganjian and T.R. Naik, paper S299, pp. 1142-1150.

[13]. WBCSD - World Business Council for Sustainable Development (2011), “CO_2 and Energy Accounting and Reporting Standard for the Cement Industry”, Version 3.0, www.wbcsdcement.org/pdf/tf1_CO_2 protocolv3.pdf, 80 p.

[14]. IPCC Garg A, Kazunari K, Pulles T (2007) “2006 IPCC Guidelines for National Greenhouse Gas Inventories”, www.ipcc-nggip. iges.or.jp/public/2006gl/vol2.html. [Accessed 31 Jan 2021]

[15]. CII-Sohrabji Godrej Green Business Centre, (2010). “Low Carbon Roadmap for Indian Cement Industry”.

[16]. MoEFCC (2018). India: Second Biennial Update Reportto the United Nations Framework Convention on ClimateChange. Ministry of Environment, Forest and ClimateChange, Government of India.

[17]. Josa A, Aguado A, Cardim A, Byars E (2007) Comparative analysis of the life cycle impact assessment of available cement inventories in the EU. Cement and Concrete Research, 37:781–788

[18]. Huijbregts, M. A., Hellweg, S., Frischknecht, R., Hendriks, H. W., Hungerbuhler, K. and Hendriks, A. J. (2010). “Cumulative energy demand as predictor for the environmental burden of commodity production”. Environmental science & technology, 44(6), 2189-2196.

[19]. Opon, J., and Henry, M. (2019). “An indicator framework for quantifying the sustainability of concrete materials from the perspectives of global sustainable development”, Journal of Cleaner Production, Vol. 218, pp. 718-737.

[20]. Bhattacherjee, S., Basavaraj, A. S., Rahul, A.V., Santhanam, M., Gettu, R., Panda, B., Schlangen, E., Chen, Y., Copuroglu, O., Ma, G., and Wang, L. (2021). “Sustainable materials for 3D concrete printing”, Cement and Concrete Composites, Vol. 122, 104156.

[21]. PRé Consultants, SimaPro LCA software, version 8.0.5.13, www.pre-sustainability.com/simapro

[22]. Central Electricity Authority (CEA), 2020, Report on fly ash generation at coal/lignite based thermal power stations and its utilization in the country for the year 2019-2020, Government of India, New Delhi. https://cea.nic.in/wp-content/uploads/tcd/2021/01/flyash_2019-20.pdf. [Accessed in January 2022]

[23]. Energy Statistics Report (2019). Central Statistics Office, Ministry of Statistics and Programme Implementation, Govermnent of India, New Delhi. (www.mospi.gov.in) http://www.indiaenvironmentportal.org.in/files/file/Energy%20Statistics%202019.pdf [Accessed in January 2022]

[24]. Hill, N., Walker, E., Beevor, J. and James, K. (2012). Guidelines to Defra/DECC’s GHG Conversion Factors for Company Reporting: Methodology Paper for Emission Factors. Department of Energy and Climate Change (DECC) and the Department for Environment, Food and Rural Affairs (Defra)’. Published by the Department for Environment, Food and Rural Affairs PB13625, United Kingdom.

[25]. Van Essen, H. (2008). “The environmental impacts of increased international road and rail freight transport–past trends and future perspectives”. In Global Forum on Transport and Environment in a Globalising World, Guadalajara, Mexico.

[26]. Prakasan, S., Panaliappan, S. and Gettu, R. (2020). "Study and Energy Use of CO_2 Emissions in the Manufacturing of Clinker and Cement", Journal of Institute of Engineers (India): Series A, 101 (1); 221-232.
[27]. Li, C., Nie, Z., Cui, S., Gong, X., Wang, Z. and Meng, Z. (2014). "The Life Cycle Inventory Study of Cement Manufacture in China", Journal of Cleaner Production, 72; 204-211
[28]. Shen, L., Gao, T., Zhao, J., Wang, L., Wang, L., Liu, l., Chen, F. and Xue. (2014). "Factory – Level Measurements on CO_2 Emissions Factors of Cement Productions", Renewable and Sustainable Energy Reviews, 34, 337-349.
[29]. Valderrama, C., Granados, R., Cortina, J. L., Gasol, C. M., Guillem, M. and Josa, A. (2012). "Implementation of Best available Techniques in Cement Manufacturing: A Life-Cycle Assessment Study", Journal of Cleaner Production, 25; 60-67
[30]. Garcia-Gusano, D., Herrera, I., Garrain, D., Lechon, Y. and Cabal, H. (2015)."Life Cycle Assessment of Spanish Cement Industry: Implementation of Environmental Friendly Solutions", 17, 59-73.
[31]. Moretti, L. and Caro, S. (2017). "Critical Analysis of the Life Cycle Assessment of the Italian Cement Industry", Journal of Cleaner Production, 152, 198-210.
[32]. Ammenberg, J., Baas, L., Eklund, M., Feiz, R., Helgstrand, A. and Marshall, R. (2015). "Improving the CO_2 performance of cement, Part III: The relevance of industrial symbiosis and how to measure its impact", Journal of Cleaner Production, 98, pp. 145-155.
[33]. Maddalena, R., Robertds, J. J. and Hamilton, A. (2018). "Can Portland Cement be Replaced by Low-Carbon Alternative Materials? A Study on the Thermal Properties and Carbon Emissions of Innovative Cements", Journal of Cleaner Production, 186, 933-942.
[34]. Feiz, R., Ammenberg, J., Baas, L., Eklund, M., Helgstrand, A. and Marshall, R. (2015b). "Improving the CO_2 performance of cement, part II: framework for assessing CO_2 improvement measures in the cement industry". Journal of Cleaner Production, 98, 282-291.
[35]. Flower, D. J. M. and Sanjayan, J. G. (2007). "Green House Gas Emissions due to Concrete Manufacture", International Journal of Life Cycle Assessment, 12(5), 282-288.
[36]. Chen, C., Habert, G., Bouzidi, Y. and Jullien, A. (2010). "Environmental impact of cement production: detail of the different processes and cement plant variability evaluation". Journal of Cleaner Production, 18(5), 478-485.
[37]. Stafford, F. N., Dias, A. C., Arroja, L., Labrincha, J. A. and Hotza, D. (2016). "Life Cycle Assessment of the Production of Portland Cement: a Southern Europe Case Study", Journal of Cleaner Production, 126; 159-165.
[38]. Berriel, S. S., Favier, A., Domínguez, E. R., Machado, I. S., Heierli, U., Scrivener, K. and Habert, G. (2016). "Assessing the Environmental and Economic Potential of Limestone Calcined Clay Cement in Cuba", Journal of cleaner Production, 124, 361-369.

Supplementary Material

Annex 1

Comparison of the Impacts of Electricity Generated in the CPPs with that Transmitted Through the Grid

The electricity transmitted through the Indian grid is produced by thermal power plants (TPPs) using fossil resources, such as coal, natural gas, crude oil, and by hydroelectric power stations, windmills, nuclear power stations. The quantities of fossil fuels used by the National Grid can be seen in Table B5, which corresponds to 2017-18. The contribution of TPPs to the generation of electricity for the grid, in the period of 2008-2018, has been reported to be 79%, with the implications shown in Figure . The losses before transmission were reported to be, on average, around 7%, and the transmission losses that occur from the source to the consumer to be, on average, about 21%, for the year 2017-18. The contribution from non-renewables can be expected to have increased since then, making grid electricity more sustainable. The CO_2 emissions associated with non-fossil fuels, i.e., from renewable sources, are considered to be low and ignored in the present analysis. The characterization factor used for each type of fuel and the corresponding source is given in Table B6.

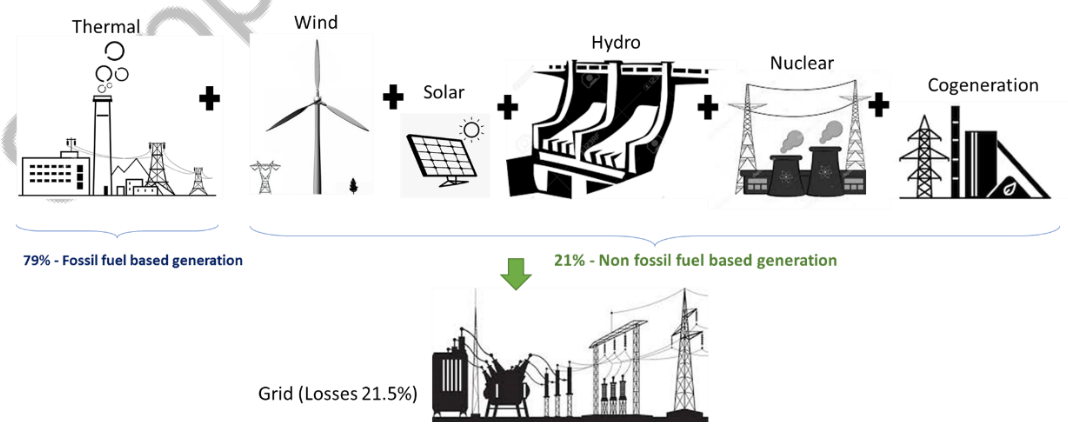

Figure 1a Electricity production mix from various sources for Indian grid [from Energy Statistics Report, 2019]

Supplementary Material

Table 1a Fossil fuels used for electricity production in utilities (for 80% of 1303 TWh) for the Indian National Grid in 2017-18

Fossil fuel	**Amount**
Coal consumption for electricity (MT)	576
Lignite consumption for electricity (MT)	38.34
Natural gas consumption for electricity (Billion cu.m.)	12.03
High speed diesel oil for power generation (kT)	211
Furnace oil for power generation (kT)	306
Light diesel oil for power generation (kT)	143
Naptha for power generation (kT)	67

Table 1b Impact characterization factors for electricity produced in CPPs and the grid

FUEL	**CO_2 emission factors**	**Source**	**Energy Content**	**Source**
Coal	1.6 kg CO_2/kg	Parikh et al., 2010	15.13 PJ/MT	Energy Statistics, 2019
Lignite	1.77 kg CO_2/kg		11.37 PJ/MT	Energy Statistics, 2019
Natural Gas	0.0021 kg CO_2/m^3		38.52 PJ/billion m^3	Energy Statistics, 2019
High Speed Diesel Oil	3.034 kg CO_2/kg	IPCC	0.0458 PJ/kT	CEA, 2005
Light Diesel Oil	3.034 kg CO_2/kg	EPA	0.0441 PJ/kT	CEA, 2005
Furnace Oil	3.038 kg CO_2/kg		0.0431 PJ/kT	CEA, 2005
Low Sulphur Heavy Stock	NA	NA	0.0437 PJ/kT	CEA, 2005
Naptha	3.12 kg CO_2/kg	IPCC	0.0472 PJ/kT	CEA, 2005
kT= kilo Tonnes; MT= Metric Tonnes; PJ = Peta Joules				

The values calculated for grid electricity, the Mettur TPP and captive power plants (CPPs) of the cement plants of this study (see Tables B1 to B4) are given in Table B7, and have

Supplementary Material

been used as the characterization factors for the impacts of electricity used in the cement production. As seen in Table B7, the impacts associated with grid electricity are seen to be generally lower those for electricity generated by the CPPs. This is mainly because of the type of coal being used as the primary fuel in the CPPs and the contribution of non-fossil sources. Nevertheless, many cement plants prefer not to use electricity from the grid due to the higher cost and to avoid interruptions in production due to frequent shutdowns. In Table 7, the impacts for the electricity from the grid for the gate-to-gate (or gate-to-consumer) system are compared with ground-to-gate (or ground-to-consumer) values taken from the ecoinvent database, through Simapro; the latter value for CO_2 emissions is similar to the value of 1.41 kg CO_2/kWh given by Hill et al. (2012) for 2010-11. The differences between the values for the two systems can be attributed mainly to the upstream processes, such as extraction and transportation of the fossil fuels, and the impacts from the electricity generated from non-fossil sources.

Supplementary Material

Table 1c Impact assessment results for electricity produced in CPPs, Mettur TPP and the grid

Plant	**Ground-to-gate**		**Gate-to-gate**	
	Emissions kg CO_2/kWh	**Embodied Energy MJ/kWh**	**Emissions kg CO_2/kWh**	**Embodied Energy MJ/kWh**
NB	2.36	22.34	1.71	15.11
MG	1.82	18.56	1.37	13.20
NM	1.81	18.65	1.34	13.43
Mettur TPP	1.46	16.81	1.03	10.35
Indian Grid# (2017-18)	1.38 Ground-to-Consumer*	19.50	0.93 Gate-to-Consumer	8.83

*From ecoinvent database; #The values include losses during transmission

The ground-to-consumer values for CO_2 emissions associated with 1 kWh of electricity supplied in different countries, as reported by Hill et al. (2012), are compared in Figure . The higher impact associated with the Indian grid electricity can be attributed to high dependence on coal and other fossil fuels, and possibly higher transmission losses compared to most other countries.

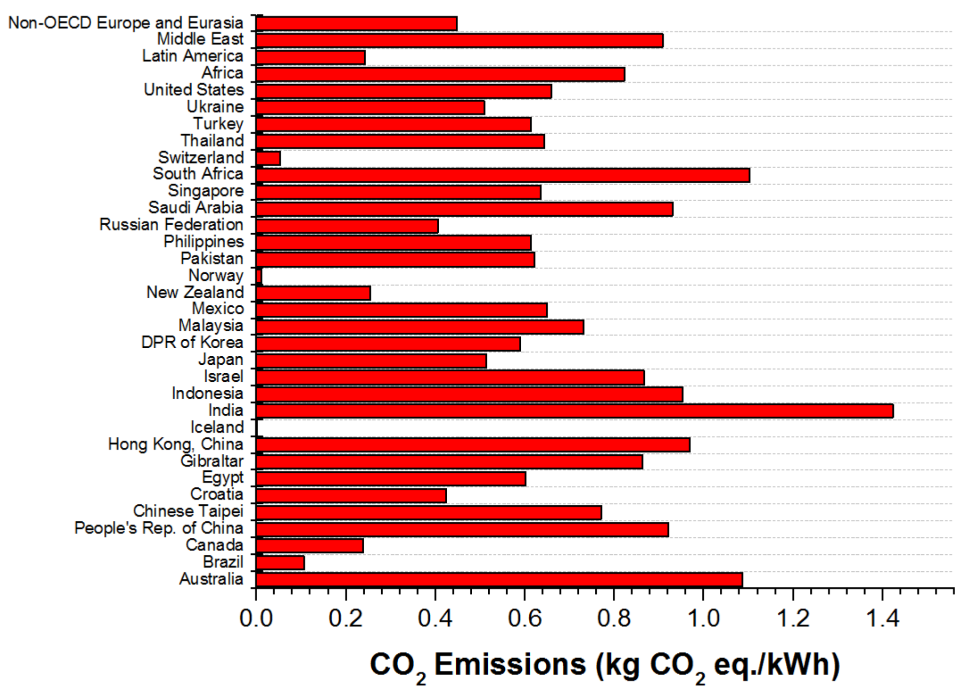

Figure 1b CO_2 footprint of grid electricity (ground-to-consumer) in different countries, with data reported by Hill et al. (2012)

Supplemental

ANNEX 2

IMPACTS OF DIFFERENT MODES OF TRANSPORTATION

For transportation by truck, the ground-to-gate system includes all the processes such as manufacturing of the vehicle, extraction of fuels, i.e., diesel, direct emissions due to diesel consumption during transportation, and the construction and maintenance of the roads used. The processes included in the ground-to-gate system of transportation through trucks are shown in Figure . Similarly, the impacts of transport by train include those related to the manufacturing of locomotives, fuel consumed for transportation, construction and maintenance of railway tracks, and the impacts of the building of the ships and port facilities, and those of the fuel used would be included in those of transportation through ships. The impacts calculated have been used as the characterisation factors in the ground-to-gate systems of the cement production for the transportation processes.

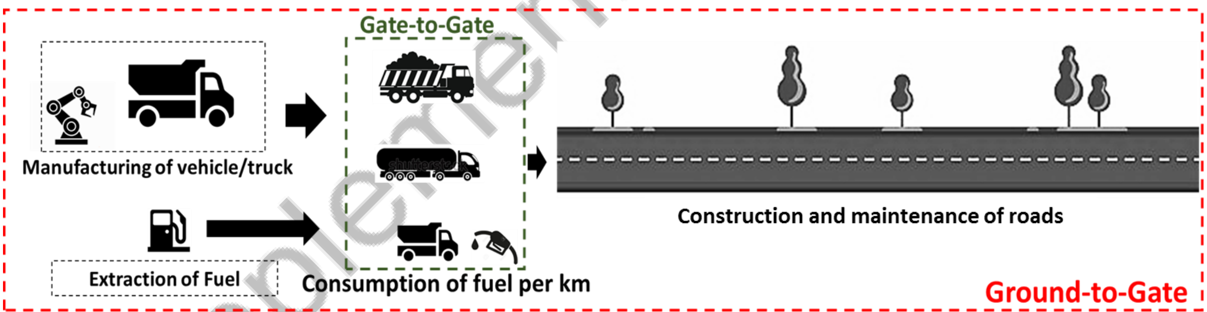

Figure 2a Processes included in transportation by trucks in different systems

The impacts of truck transportation in the gate-to-gate system are seen to be much lower than that of the ground-to-gate system as upstream processes, such as manufacturing of the truck, extraction of fuel and construction and maintenance of roads, are not considered. Note that transportation by ship and train are not considered in the gate-to-gate system.

Supplementary Material