Deterministic approach for calculation of Carbon Footprint for Cement plants in India

Amit K. Shrivastava*, Aman Vashishth¹, Bhagya Jayant²

* Faculty, Department of Civil Engineering, Delhi Technological University, Delhi, India, aksrivastava@dce.ac.in
¹ Student of Environmental Engineering, Delhi Technological University, Delhi, India, amanvashishth20@gmail.com
² Student of Civil Engineering, Delhi Technological University, Delhi, India, bhagyajayant1822@gmail.com

ABSTRACT

Estimating cement process emissions through an industry’s dataset has more often if not always been majorly based on strong assumptions. India being the second largest producer of cement across the globe next only to China, lags in providing accurate estimates of its official time-series to UNFCCC (United Nations Framework Convention on Climate Change).

Present study has been undertaken to lay out a deterministic approach for calculation of carbon footprint for any Indian Cement Plant using the customized design methodology. Modelling of which is done by referring to and prioritizing various companies’ official data, emission factors, and cement protocols. The framework aligns itself to Greenhouse Gas Protocol and Cement Sector Emissions Calculation Tool: Indian Version 1.0 (July 2005) and CO₂ Accounting and Reporting Standard for the Cement Industry, The Cement CO₂ Protocol, Version 2.0 (Cement Sustainability Initiative, June 2005). It aims to provide a more reliable source for estimation of greenhouse gas - CO₂ emissions in any cement processing plant of India.

Index Terms – CO₂ emissions, Direct & indirect emissions, cement production

I. INTRODUCTION

India is the second-largest cement producer in the world next only to China (Indian Cement Industry Analysis, IBEF, 2021). Accounting for more than 8% of the total installed capacity across the globe (2019), its cement production capacity in FY20 was reported to be about 545 MT (Indian Cement Industry Analysis, IBEF, 2021). The Indian cement industry comprises of 210 cement plants; in a total of which 77 are established in Andhra Pradesh and Tamil Nadu (Indian Cement Industry Analysis, IBEF, 2021). An increase in the installed capacity for cement production is expected to be about 800 MTPA by the year 2030 (Cement, Bureau of Energy Efficiency, 2021). Investment in cement and gypsum attracted US $5.28 billion from April 2000 to March 2020 (DPIIT, IBEF, 2021) and the demand is still high.

Cement production is a major source for greenhouse gas emissions contributing towards CO₂ emissions in majority. According to the Indian Cement Industry report, India’s greenhouse gas emission intensity value ranges from 560 kg CO₂/ ton of cement produced to 687 kg CO₂/ ton of cement produced (CII, 2010). Being the largest man–made material in the world, cement is linked relentlessly to Climate Change responsible for health problems and deaths related to air pollution. Economic degradation due to the exponential expense burden in the healthcare department is another consequence. Carbon dioxide is majorly produced as a by-product of clinker production in the process of cement manufacture and as energy produced in fossil fuels. However, the dependence on meeting the global economic productions through energy from combustion of fossil has detritus effects expected to harm global welfare and diminish economic productivity.

II. LITERATURE REVIEW
The industrial and energy sources in cement production contribute to approximately 2.4% of the global carbon dioxide emissions (Marland et al., 1989). As per estimations, 0.5 to 0.9 kg of CO$_2$ is emitted on the production of 1 kg of cement (Gartner, 2004). 90% of the energy required for cement manufacturing is met out of fossil fuels while the remaining 10% is met whence electricity. (C. A. Hendriks et. al., 2004). Besides, E. Benhelal et al., (2013) reasoned out the estimation of global CO$_2$ emissions from the cement industry at 5% to Portland cement manufacturing and the use of outdated industrial equipment responsible for the consumption and the consequent evolution of huge amounts of particulate matter. And even though the latest technologies have increased the production efficiency of cement production, there has been a significant rise in CO$_2$ emissions as a consequence of increased demand for development in infrastructure. (G. U. Fayomi et al., 2019).

**Cement Processing in a Plant**

Cement is a binding material used for construction to bind the materials together. It is generally used to bind sand and gravel together to manufacture concrete and with fine aggregates to manufacture mortar or masonry. Every cement plant undergoes the steps shown in Fig. 1 for the manufacturing of cement.

![Cement manufacturing processes in a cement plant](https://i.imgur.com/5.png)

*Fig. 1 – Cement manufacturing processes in a cement plant
(Encyclopedia Britannica, Inc., 2007)*

**Carbon capture in Cement manufacturing plant**
The reaction begins at the limestone quarry. The limestone near the surface has a high content of minerals like silica, iron and aluminum oxide. On going at a further depth, we find more of CaCO$_3$ content. The first carbon footprint counts or carbon capture is marked here; in making a big hole using machines which take up a lot of energy. Limestone found in mines are then drilled to smaller sizes in the process of quarrying.

Next, the detonator is fixed and the holes are digged in the ground and plant-powerful explosives are set up for blasting. (Maintaining a distance of at least 50m). Here, the second carbon capture is observed. For emissions from blasting which include CH$_4$ and CO$_2$ emissions from natural gas extraction, CO$_2$ emissions from ammonia production and the emissions from the actual blasting.

After blasting, the material is filled in the dumper using an excavator which is weighed at the cement plant to determine the amount of raw material for the plant. After the explosion the loaders move in, they transfer the limestone rock to a dump truck. At the plants, the trucks, dump the rocks in the primary crusher. The primary crusher reduces the material to smaller sizes. There is a constant spray of water to keep the dust from billowing up and settling on the shoots. This conversion also gives out a lot of energy marking as the third carbon capture.

Next, the limestone is fed in the crusher which is sent to the compound impact cursor using a conveyor. The material is crushed using limestone crusher to finer sizes (25 mm or 30 mm) depending upon the available mill as vertical roller mill or ball mill. Rocks with high calcium carbonate and rocks low in calcium carbonate are crushed separately. Then it’s mixed. This overhead machine also known as the tripper then makes piles of the required proportions known as the raw mix. A reclaimer loads this raw mix into a grinding machine called a roller mill. The factory or plant adds extra minerals such as silica and iron. Certain types of cement also require aluminum oxide. The roller then mixes and grinds the ingredients uniformly producing a dry rock powder called the raw meal. More crushing implies more energy and all the added minerals have their own associated emissions thereby marking the fourth carbon capture.

Now the powder goes into the pre-heater, the temperature of which is 80°C upon entering. Within 40 seconds it gets more than ten times hotter, releasing a lot of energy responsible for fifth carbon capture in the plant. This begins the process of bonding the minerals together so that they later harden when hydrated with water.

The preheater is equipped with a flash calcine. In about 5s it removes about 95% of the CO$_2$ and the powder through a chemical reaction isolates the lime which is the most important element in the cement. In 5s, 95% of the fixed CO$_2$ is released in the atmosphere which had been stripped from the limestone fixed in the rock for over 100 million years, polluting it and marking the sixth carbon capture.

From here the powder moves into the rotary kiln which is a huge cylindrical furnace. It is set at an angle so that the powder moves a distance of about 49 m from top to bottom. The kiln rotates about two turns a minute to ensure the material travels through at a right speed. The burner gas flame at the bottom reaches a scorching 1600°C – 1700°C. As the powder approaches or cools down to a 1500°C mark, it fuses into pieces with a diameter of about 5 cm approximately. These pieces are called clinkers. As the clinker leaves the kiln, large fans further cool it down to a temperature range of 60°C – 80°C. It is important to cool the clinker quickly in order to have quality cement. According to IPCC (Intergovernmental Panel on Climate Change, 2008) every 1 ton of clinker releases 1.25 tons of CO$_2$ in the atmosphere. Thereby making this stage as the eighth carbon capture.

From here, the clinker goes to the storage area. This process requires tons of fossil fuels to release CO$_2$ from clinkers marking the seventh carbon capture. This also explains the reason behind cement plants produce more CO$_2$ emissions than cement.

The last stage of cement processing is finish grinding. In this stage, gypsum is added to the clinker. Gypsum delays the cement's initial setting time so that it can be worked for up to 2 hours before hardening. The material after being crushed is transported using a conveyor belt to the pile yard for stocking. Here, the material is homogenized using the reclaimer and scraping chain along the belt conveyor. This is the final and the eighth carbon capture concluding the cement manufacturing, transporting and storing process in the plant in complete totality.
III. OBJECTIVE

This study has been intricately performed to overcome the problem of data unavailability for calculating CO₂ emissions in the processing of cement in India. It has been resolved by factually analyzing the various cement-manufacturing industries’ official data, emission factors, and cement protocols with reduced assumptions for better accuracy. As a consequence, a customized framework has been designed with the aid of Greenhouse Gas Protocol and Cement Sector Emissions Calculation Tool: Indian Version 1.0 (July 2005) and CO₂ Accounting and Reporting Standard for the Cement Industry, The Cement CO₂ Protocol, Version 2.0 (Cement Sustainability Initiative, June 2005). The framework has been broadly classified into Scope 1 and Scope 2 for calculation of direct CO₂ emissions and indirect CO₂ emissions respectively in various cement-manufacturing plant units. It is a user-friendly algorithm that may be utilized as a guide for computation of the carbon footprint of Indian cement plant(s). This can be done by performing certain alterations throughout the framework after the assembling of scrutinized plant-specified data.

IV. METHODOLOGY

The framework generated in this paper is compatible with the latest guidelines for national greenhouse gas inventories issued by IPCC (Intergovernmental Panel on Climate Change) and with the revised WRI / WBCSD Protocol. The framework has been developed with the aid of Greenhouse Gas Protocol and Cement Sector Emissions Calculation Tool: Indian Version 1.0 (July 2005), an algorithm developed by the World Resource Institute (WRI) also called as the Indian Cement tool and CO₂ Accounting and Reporting Standard for the Cement Industry, The Cement CO₂ Protocol, Version 2.0 (Cement Sustainability Initiative, June 2005) which is intended as a tool for cement companies worldwide inclusive of calculations for direct and indirect CO₂ emissions. The companies undertaken must include activities such as clinker production, including raw material quarrying, grinding of clinker, additives, and cement substitutes such as slag, both in integrated cement plants and stand-alone grinding stations in the voluntary calculation using this framework. The framework is ideal for calculating the carbon footprint of any Indian cement plant/industry and may be used for further investigation or exploration in the same field.

Framework

The framework breaks down the scope of calculating CO₂ emissions into Scope 1 and Scope 2 based on direct CO₂ emissions and indirect CO₂ emissions from cement processing in the industry respectively.

Scope 1 – Direct CO₂ emissions

Direct CO₂ emissions are those that are generated from sources owned or controlled by the cement-producing companies. These emissions are primarily a result of CO₂ emissions attributed to the calcination of raw materials and fuel combustion. Calcination is the process of transforming raw materials into clinker. And, fuel combustion is the process of burning the fuels (oil, coal, petrol coke, etc.) in kilns and mobile combustions. Also, the scope takes into consideration emissions from the organization’s vehicles and (if any) refrigerant – leaks on site. In short, all on-site emissions are accounted for in Scope 1. The in-depth discussion regarding these sources and their calculations has been done and performed in the coming sections subcategorized into –

- Scope 1.1 – CO₂ from raw materials
- Scope 1.2 – CO₂ from direct stationary combustion
- Scope 1.3 – CO₂ from mobile combustion

Scope 1.1 – Calculating CO₂ emissions from raw material

The emissions from scope 1.1 originate from the calcination of clinker, calcination of dust, and organic carbon in the raw material. Calcination is defined as the purification process of heating (oxidizing) the raw materials at a high temperature to remove the volatile materials from the mass. Cement process CO₂ emissions mainly from calcination of calcium carbonate (CaCO₃) and magnesium carbonate (MgCO₃) in the raw meal for clinker production, which can be expressed by the following chemical equations (Worrell et al., 2001).
CaCO$_3$ $\rightarrow$ CaO + CO$_2$ \hspace{1cm} (1)

MgCO$_3$ $\rightarrow$ MgO + CO$_2$ \hspace{1cm} (2)

Using the relative formula mass $M_r$, the above chemical equations can be rewritten accordingly to the suit the law of conservation of matter.

$$M_r (\text{CaCO}_3) = M_r (\text{CaO}) + M_r (\text{CO}_2)$$ \hspace{1cm} (3)

$$M_r (\text{MgCO}_3) = M_r (\text{MgO}) + M_r (\text{CO}_2)$$ \hspace{1cm} (4)

Where, $M_r$ is the molar mass

$M_r (\text{CaCO}_3) = 100.09$ u

$M_r (\text{MgCO}_3) = 84.31$ u

$M_r (\text{CaO}) = 56.08$ M_r (MgO) = 40.30 u

$M_r (\text{CO}_2) = 44.01$ u

From the above equations, it is observed that the calcination of 1 ton (t) of CaCO$_3$ emits about 0.44 t of CO$_2$, and the calcination of 1 t of MgCO$_3$ emits about 0.52 t of CO$_2$.

Generally, there are two types of widely – accepted and often – used calculation methods for estimating the processed CO$_2$ emissions from cement production: the input method (raw materials or raw meal in particular) and the output method (clinker method and cement method) (CSI, 2011). In this framework, the output methods have been included which are the Clinker – based approach and Cement-based approach. Either of the two methods may be used depending upon the availability of data from the company for calculating direct CO$_2$ emissions from raw materials.

The framework is designed for the annual production of Ordinary Portland Cement (OPC) in cement manufacturing companies. The amount of Cement produced is assumed to be 1 ton. This standard value can be multiplied with the data from the cement company and consecutive changes may be made throughout the framework for calculation purposes. Besides, alteration may be done to the framework for different types of cement, plant-specific values for emissions, and much more. For reference, the framework is inclusive of certain parameters intricately yet sequentially mentioned throughout the framework.

Considering the average CO$_2$ emission factor for clinker (EF$_{\text{Cl}}$) equal to 0.528 t CO$_2$ / t clinker (Indian Cement tool, [6]), on an average the production of 1 ton of cement releases 1.25 tons of CO$_2$ (IPCCC, 2018).

- 1 tons of cement $\rightarrow$ 1.25 tons of CO$_2$
- 1 ton of clinker (releases) $\rightarrow$ 528 kg of CO$_2$ = 0.528 tons of CO$_2$

From the above equations,

- 1 ton of CO$_2$ is released from $\rightarrow$ (1/0.528) tons of clinker
- 1 ton of CO$_2$ is released from $\rightarrow$ 1.893 tons of clinker
- 1.25 ton of CO$_2$ is released from $\rightarrow$ 1.893 x 1.25 tons of clinker

1 tons of cement $\rightarrow$ 2.36 tons of clinker $\rightarrow$ 1.25 ton of CO$_2$

Therefore, average amount of clinker produced for 1 ton of cement production = 2.36 tons.

(I) Clinker – based approach
This approach calculates CO₂ emissions from cement production based on the CaO and MgO content and the amount of clinker thereby produced. This method involves estimating process-related CO₂ emissions from cement production.

**Step 1:** Consider the amount of clinker produced \( (P_{\text{Cli}}) = 2.36 \text{ tons} \) (assumption, from eq. (5))

**Step 2:** Average CO₂ emission factor for clinker \( (EF_{\text{Cli}}) = 0.528 \text{ t CO}_2 / \text{ t clinker} \) (Indian Cement tool, [6])

**Step 3:** The amount of CKD lost in the absence of plant – specific value may be considered as 2% of CO₂ released from clinker production. (from eq. (5), CSI, [7])

Therefore, the amount of CKD lost = \( (0.02) \times (1.25) = 0.025 \text{ tons} \)

**Step 4:** Average CO₂ emission factor for CKD \( (EF_{\text{CKD}}) = 0.4514 \text{ t CO}_2 / \text{ t CKD lost} \) (Indian Cement tool, [6])

**Step 5:** Let the total CO₂ emissions from Scope 1.1 be \( X_1 \). (Indian Cement tool. [6])

\[
X_1 = 2.36 \times 0.528 + 0.025 \times 0.4514 = 1.257 \text{ CO}_2
\]

Let CO₂ emissions per ton of raw material (clinker) used be \( A \)

\[
A = 1.257 / 2.36 = 0.5327 \text{ t CO}_2
\]

In the absence of plant – specific value, the value of \( A \) shall be directly multiplied with the amount of clinker produced (in tons). In which case, the intermediate steps may be skipped. However, one should ensure that when doing so the assumptions mentioned in the beginning of the framework are matched.

(I) **Cement – based approach**

Since different types of cement contain varying clinker fractions, it is important to segregate cement production data by its cement type. In the cement-based approach, the data should be reported separately for Ordinary Portland Cement (OPC), Pozzolana Portland Cement (PPC), Portland Slag Cement (PSC), and other cement types. Some of the default clinker fractions based on the assumed cement type blends can be used as given in Table 1 (Indian Cement Tool, [6]). This method involves estimating process-related CO₂ emissions from cement production.

| S. No. | Cement Type                              | Clinker to cement ratio (%) |
|-------|------------------------------------------|-----------------------------|
| 01    | Ordinary Portland cement (100% Portland output) | 95                          |
| 02    | Portland Pozzolana Cement                | 75                          |
| 03    | Portland Slag Cement                     | 55                          |

**Step 1:** Consider the amount of cement produced = 1 ton (assumption, eq. (5))

**Step 2:** Clinker to cement ratio = 0.95 (OPC, Table 1)

**Step 3:** Total clinker that is released from just the cement production may be calculated as:

\[
(\text{Total clinker from cement production only}) = (\text{amount of cement produced}) \times (\text{clinker to cement}) \quad (6)
\]
Step 4: Consider the amount of clinker imported and exported. Assuming that no clinker has been imported or exported to the plant. Therefore, amount of clinker imported and exported = 0.

Step 5: Total clinker produced in the company / facility / plant is calculated as below. (Indian Cement tool, [6])

\[
\text{(Total clinker from cement production)} - \text{(imported clinker)} + \text{(exported clinker)}
\]

= 0.95 tons of clinker

Step 6: To determine the amount of raw materials used and then calculate ton of raw material per ton of clinker on dividing. In the absence of plant – specific value for raw material or import and export clinker amounts, the default value of 1.5 can be considered.

Therefore, \( \frac{\text{(t of Raw material)}}{\text{(t of Clinker)}} = 1.5 \) (Indian cement tool, [6])

Step 7: To determine the amount of CaCO\(_3\) equivalent used to produce clinker, calculated as –

\[
\text{(CaCO}_3\text{ equivalent raw material ratio, %)} = \frac{\text{(CaCO}_3\text{ equivalent for raw material)}}{\text{(amount of raw material)}}
\]

In the absence of plant – specific value, consider the default value of CaCO\(_3\) equivalent raw material ratio as 0.78. (India Cement Tool, [6])

Step 8: Finally, let the total CO\(_2\) emissions (in tons) be \( X_1' \)

\[
X_1' = P_{\text{cement}} \times \text{(clinker/cement)} \times \text{(RM/clinker)} \times \frac{\text{(CaCO}_3\text{ equivalent/ RM)}}{\text{(MW CO}_2/\text{MW CaCO}_3)}
\]

where RM = Raw Material and MW = Molecular Weight (Indian cement tool, [6])

The stoichiometric ratio of CO\(_2\) to CaCO\(_3\) = \( \frac{44}{100} = 0.44 \)

\[
= 1 \times 0.95 \times 1.5 \times 0.78 \times 0.44
\]

\[
= 0.489 \text{ tons of CO}_2 \text{ emissions}
\]

Let the CO\(_2\) emissions per ton of raw material (cement) used be B.

Then, \( B = 0.489 \text{ kg CO}_2 / \text{ton} \)

In the absence of plant – specific value, the value of B shall be directly multiplied with the amount of cement produced (in tons). In which case, the intermediate steps may be skipped. However, one should ensure that when doing so the assumptions mentioned in the beginning of the framework are matched.

**Scope 1.2 – Calculating CO\(_2\) emissions from direct combustion**

When the raw material is fed into the preheater rotary kiln, the conventional kiln fuels like anthracite, bituminous, and coke, alternative fossil fuels like natural gas, biomass fuels, non – kiln fuels like NO\(_X\), and
wastewater in combusted; all of which come under scope 1.2. In this scope, the steps represented in Table 2 below are used to calculate CO₂ emissions from each fuel.

**Table 2: Step – by – step procedure for calculation of scope 1.2 CO₂ emissions**

| S. No. | Fuel          | Quantity of fuel burned (in tons) (I) | Calorific value of fuel (in GL/ tons) (II) | CO₂ Combustion Factor (in kg CO₂/ GJ) (III) | Oxidized carbon fraction (IV) | Total CO₂ emissions from fuel (in kg) (= I x II x III x IV) |
|--------|---------------|--------------------------------------|---------------------------------------------|---------------------------------------------|-------------------------------|----------------------------------------------------------|
| Eg     | Bamboo Dust   | 45000                                 | 15.25                                       | 96.10                                       | 1.00                          | 66,948,625                                                |

Σ = ...........

The above table for individual fuel calculations has also been represented in steps below. The total CO₂ emissions contributing towards scope 1.2 is the summation of CO₂ emissions from each fuel. (Indian Cement tool, [6])

**Step 1:** Consider the quantity of fuel burned (in tons)

**Step 2:** Average net calorific value in GL/ tons (plant – specific/ default value)

**Step 3:** Calculate quantity of fuel used in energy (in GJ) (using the formula) (Indian Cement tool, [6])

\[
\text{Quantity of fuel used in energy} = (\text{Quantity of fuel burned}) \times (\text{Average net calorific value})
\]

**Step 4:** Take CO₂ combustion emission factor specific to fuel (kg CO₂/ GJ) (plant – specific/ default value)

**Step 5:** Consider the oxidized carbon fraction. In case of unavailability of this value, certain default values are given below.

**Table 3: Default value for oxidized carbon fraction based on fuel type**

| S. No. | Fuel type | Oxidized carbon fraction |
|--------|-----------|-------------------------|
| 01     | Coal/ Lignite used in kiln of pre – calcinator | 1.00 |
| 02     | Coal used in other furnaces                     | 0.98 |
| 03     | Oil                                               | 0.99 |
| 04     | Gas                                               | 0.995 |

(Reference – Indian Cement tool)

**Step 6:** Therefore, CO₂ emissions (in kg) (Indian Cement tool, [6])

\[
\text{CO}_2 \text{ emissions} = (\text{Quantity of fuel used in energy}) \times (\text{CO}_2 \text{ combustion emission factor}) \times (\text{oxidized carbon fraction})
\]

\[
\text{CO}_2 \text{ emissions} = \ldots \ldots \text{kg CO}_2 \text{ emissions} = \ldots \ldots \text{tons CO}_2 \text{ emissions}
\]

The summation of CO₂ emissions from each fuel type contributes towards the total CO₂ emission in Scope 1.2. Let X₂ be the total CO₂ emissions from Scope 1.2. Therefore, \(X_2 = \sum (\text{fuel emissions, tons}).\)

**Scope 1.3 Calculating CO₂ emissions from direct mobile combustion**

In this framework, we have only considered the transportations wherein the vehicles are owned or controlled by the reporting entity or the company under consideration. The cement production process involves the transportation of raw materials, fuels, and the distribution of finished goods. The transportation modes can be railways, waterways, and/or roadways; each of which emits CO₂ which is accounted for under this scope. The following diagram highlights the inclusivity of Direct and Indirect emissions from the on-site emissions from transportation in the framework.
Table 4 also later represented in steps are used to calculate the CO₂ emissions for each vehicle and its corresponding fuel type. These steps are repeated for each vehicle type and the results for each cycle are added. The summation of the final CO₂ emissions for each vehicle type results in the total CO₂ emissions contributing towards Scope 1.3. This can be calculated either using distance travelled by the vehicle or through its fuel consumption details.

**Method 1: CO₂ emissions from fuel consumption in the vehicle(s)**

When fuel consumption data for a vehicle is available

| S. No. | Transport Description | Fuel type Used | Fuel consumption or quantity of fuel burned (L) | CO₂ emission factor (in kg CO₂ / L) | Oxidized carbon fraction (default value) | Total CO₂ emissions (tons) |
|--------|-----------------------|----------------|-----------------------------------------------|-------------------------------------|----------------------------------------|--------------------------|
| E.g.   | Loader                | Diesel         | 5000                                          | 0.1005                              | 0.99                                   | 502.5                    |

Σ = ............

**Step 1:** Collect data regarding the vehicle type, fuel used, its fuel consumption, CO₂ emissions factor for the fuel type in vehicle type.

**Step 2:** Taking default value of oxidized carbon fraction as 0.99 (Indian Cement tool, [6])

**Step 3:** Let the total CO₂ emissions (in tons) be X₃, then using the formula – (Indian Cement tool, [6])

\[ X₃ = \text{(Fuel consumption} \times \text{CO₂ emission factor} \times \text{oxidized carbon fraction}) / 1000 \] (12)

**Method 2: CO₂ emissions from distance – travelled by the vehicle(s)**

| S. No. | Transport Description | Distance travelled on-site (km) | CO₂ emission factor (in kg CO₂ / km) | Total emissions (in kg) |
|--------|-----------------------|---------------------------------|--------------------------------------|-------------------------|
| E.g.   | Loader                | 5000                            | 0.1005                               | 502.5                   |

Σ = ............

**Step 1:** Collect the data regarding the vehicle and fuel type, quantity of such vehicle types like trucks, cars, dumpers, loaders,
and more visiting the site per day, the average distance travelled by it on-site in a year, and the specific CO\textsubscript{2} emission factor corresponding to the vehicle and fuel type.

**Step 2:** The total CO\textsubscript{2} emissions from mobile combustion of each vehicle is calculated as below. (Indian Cement tool, [6])

\[
\text{Total CO}_2 \text{ emissions from mobile combustion} = (\text{Distance travelled}) \times (\text{CO}_2 \text{ emission factor})
\]

\[
= \ldots \ldots \text{kg} = \ldots \ldots \text{tons}
\]

Let total CO\textsubscript{2} emissions from scope 1.3 emissions be \(X_3\).

Therefore, \(X_3 = \Sigma \text{(emissions from each vehicle type)}\)

**Total CO\textsubscript{2} emissions from SCOPE 1**

Let total CO\textsubscript{2} emissions from scope 1.1, 1.2 and 1.3 will be \(X\).

Thus, \(X = X_1 + X_2 + X_3\)

**Scope 2 – Indirect CO\textsubscript{2} emissions**

An organization may use energy that doesn’t generate emissions onsite. However, the creation of electricity and its distribution results in emissions that are off-site (from the power plant). It should be noted that electricity emissions vary greatly because of the fuel used to produce electricity. For e.g., Coal produces the most emissions because it is not a clean fuel. Electricity can also be generated from heavy furnaces, oil, or gas which are relatively cleaner. The cleanest source of electricity is renewables.

Table 6 also latter represented in step below can be used for calculating the contribution of CO\textsubscript{2} emissions for each stream description. The total CO\textsubscript{2} emissions contributing towards scope 2 will be the summation of all CO\textsubscript{2} emissions from electricity consumption (\(\Sigma\)).

**Table 6: Step – by – step procedure for calculation of scope 2 CO\textsubscript{2} emissions**

| S. No. | Description | Electricity Purchased (in kWh) (I) | CO\textsubscript{2} emissions Factor (in g CO\textsubscript{2}/kWh) (II) | Indirect CO\textsubscript{2} Emissions (in tons) (= I x II) |
|--------|-------------|-----------------------------------|-------------------------------------------------|-------------------------------------------------|
| E.g.   | --          | 80000000                         | 806                                             | 64480                                           |

**Step 1:** Consider the emission factor based on the location of the industry (Indian Cement tool. [6])

**Step 2:** Take average electricity purchased in kWh for a year (plant – specific value)

**Step 3:** Therefore, CO\textsubscript{2} emissions from each electricity consumption activity is calculated as below. (14)

\[
\text{CO}_2 \text{ emissions from each electricity consumption} = ((\text{Electricity purchased}) \times (\text{CO}_2 \text{ emission factor})) / 1000000
\]

\[
= \ldots \ldots \text{Tons}
\]

Let the total CO\textsubscript{2} emissions from scope 2 be \(Y\)

Then, \(Y = \Sigma \text{(CO}_2 \text{ emissions from each electricity consumption activity)}\)

**Calculating total carbon footprint**
Calculating carbon footprint = CO$_2$ emissions produced by the industry in a year = (X+Y) = .......... tons per annum

V. CASE STUDY

To substantiate the credibility of this framework, let’s calculate the CO$_2$ emissions for the following case study of one of the leading cement-manufacturing companies in India. The results of which would later be tallied with the actual reporting data/figures acquired from their official websites. For simple yet efficient processing of the entire framework which is easy to understand, certain assumptions would be made in the progression.

Assuming the company’s name is ABC.

Background of company ABC – one of the leading cement-manufacturing companies in India

ABC company has its roots all across India with 17 cement manufacturing units, 90 ready – mix concrete plants with over 6600 employees and vast distribution network of 50,000 + dealers. The cement type manufactured in ABC is Ordinary Portland Cement (grade 53 and grade 43) in the bag size of 50 kg. The CO$_2$ emissions calculated for the inputted data for the year 2018.

For Scope 1.1 – CO$_2$ emissions from raw materials (Using Cement – based approach)

Due to the unavailability of the clinker data for the company, the cement – based approach has been opted for calculating CO$_2$ emissions from raw materials.

Step 1: Total amount of cement – produced = 33.05 MT (installed cement capacity, Sustainability Report, 2019)

Step 2: Clinker to cement ratio = 95% (Indian Cement tool, [16])

Step 3: Therefore, the clinker used for the cement production (in tons) using formula –

\[
\text{(Total clinker used for cement production)} = \text{(cement produced)} \times \text{(clinker to cement ratio)}
\]

\[
= (33.05) \times (-0.95) = 31.395 \text{ tons’ clinker}
\]

Step 4: Imported clinker and exported clinker = 0 (no data available)

Step 5: Therefore, total clinker produced in the facility/plant

\[
= (\text{total clinker used for cement production}) - (\text{imported clinker}) + (\text{exported clinker})
\]

Step 6: The raw materials and their amounts used are listed as below. (ABC Sustainability Report)

| Table 7: Quantity of raw materials used for manufacturing of OPC cement in ABC company |
|---|
| S. No. | Raw material | Quantity (in MT) |
| 01 | Limestone | 24.86 |
| 02 | Gypsum | 1.18 |
| 03 | Alternate materials | 3.37 |
| 04 | Slag | 3.18 |
| 05 | Fly ash | 5.74 |
| 06 | Additives | 0.10 |
| 07 | Others | 1.67 |
| Σ = 37.1 MT | | |
Other raw materials like lubricating oil, grease are proportionately very small and hence neglected for calculations.

Therefore, the amount of raw materials used for manufacturing of cement = 37.1 MT

**Step 7:** The amount of CaCO$_3$ used to produce clinker

\[ \text{Amount of CaCO}_3 \text{ used to produce clinker} = \left( \frac{\text{CaCO}_3 \text{ equivalent}}{\text{raw material}} \right) \times (\text{amount of raw material}) \]

The default value of ratio of CaCO$_3$ to raw material is considered, since the plant-specific value is not available. Implying, \(\left( \frac{\text{CaCO}_3 \text{ equivalent}}{\text{raw material}} \right) = 0.78\). (Indian Cement tool [16])

\(\text{Amount of CaCO}_3 \text{ used to produce clinker} = (0.78) \times (37.1) = 28.93 \text{ MT CaCO}_3\)

**Step 8:** Finally, the total CO$_2$ emissions (in tons) is given by the formula -

\[ \text{Total CO}_2 \text{ emissions} = P_{\text{cement}} \times \frac{\text{clinker}}{\text{cement}} \times \frac{\text{RM}}{\text{clinker}} \times \frac{\text{CaCO}_3 \text{ equivalent}}{\text{RM}} \times \left( \frac{\text{MW of CO}_2}{\text{MW of CaCO}_3} \right) \times 10^6 \text{ MT CO}_2 \text{ emissions} \]

\[ = (33.05) \times (0.95) \times (37.1/31.395) \times (28.93/37.1) \times (44/100) \times 10^6 \text{ MT CO}_2 \text{ emissions} \]

\[ = 12.5 \text{ MT CO}_2 \]

Therefore, \(X_1^* = 12.5 \text{ MT CO}_2\)

**For Scope 1.2 – CO$_2$ emissions from direct stationary combustion (fuel combustion)**

Combustion of the kiln (conventional and alternative), and non – kiln fuels for ABC and their respective energy consumptions have been listed in Table 8 and Table 9 respectively. The individual values of the quantity of fuel used, their calorific values, and the oxidized fraction are not available. However, the data for the energy consumption by each fuel is available. It can be expressed as below.

\[
\text{Energy consumption} = (\text{Quantity of fuel burned}) \times (\text{calorific value of fuel}) \times (\text{oxidized carbon fraction})
\]

(15)

Now using the framework, and representing the steps for calculations under scope 1.2 in tabular form under Table 8 and Table 9 with a combined column for Energy consumption.

1. **CO$_2$ released from conventional and alternative kiln fuels**

The kiln fuels used by the company are listed as below.

**Table 8: Step – by – step procedure for calculation of ABC CO$_2$ emissions from kiln fuels**

| S. No | Fuel                | Energy consumed (in TJ) | Energy consumed (in GJ) $\times 10^3$ (I) | CO$_2$ combustion factor (kgCO$_2$/GJ) (II) | COLUMNA | Total CO$_2$ emissions (kg) $= (I) \times (II)$ |
|------|---------------------|------------------------|------------------------------------------|--------------------------------------------|---------|------------------------------------------|
| 1.   | Pet coke + coal     | 51,417                 | 51417000                                 | 107.738                                    | 5539564746 |
| 2.   | Diesel oil          | 62                     | 62000                                    | 73.84                                      | 4578080  |
CO\textsubscript{2} released from conventional and alternative fuels = Σ (COLUMN A) = 578560266 kg = 5.785 MT CO\textsubscript{2}

2. CO\textsubscript{2} released from non-kiln fuels

The non-kiln fuels used by the company are listed as below.

| S. No | Fuel                | Energy consumed (TJ) | Energy consumed (in GJ) x 10\textsuperscript{3} (I) | CO\textsubscript{2} combustion factor (kgCO\textsubscript{2}/GJ) (II) | COLUMN B Total CO\textsubscript{2} emissions (kg) = (I) x (II) |
|-------|---------------------|----------------------|------------------------------------------------------|-------------------------------------------------|--------------------------------------------------|
| 1.    | Pet coke + coal     | 24,510               | 24510000                                             | 107.738                                         | 2640658380                                       |
| 2.    | Diesel oil          | 7                    | 7000                                                 | 73.84                                           | 516880                                           |
| 3.    | Biomass fuels       | 100                  | 100000                                               | 69.98                                           | 6998000                                          |
| 4.    | Alternative fuels   | 167                  | 167000                                               | 112.45                                          | 18779150                                         |

CO\textsubscript{2} released from non-kiln fuels = Σ (COLUMN B) = 2666952410 kg = 2.667 MT CO\textsubscript{2}

Thus, the total CO\textsubscript{2} emissions from scope 1.2 (X\textsubscript{2}) = Σ (COLUMN A + COLUMN B) = 5.785 + 2.667

Therefore, X\textsubscript{2} = 8.452 MT CO\textsubscript{2}

For Scope 1.3 – CO\textsubscript{2} emissions from direct mobile combustion

Major contribution towards production of CO\textsubscript{2} emissions in the company/industry has been from the truck. Assuming the truck to be of an average weight of 16 tons with 4 km per liter mileage. (Assumptions, [11])

Using Method 2 – CO\textsubscript{2} emissions from distance travelled by the vehicle
Here, the truck with diesel is travelling on – site which is responsible for CO2 emissions based on distance travelled on-site. The default value for diesel is taken to be 74.01 kg CO2/ GJ (Indian Cement tool, [6])

By stoichiometry,
- 1 GJ energy of diesel (generates) \( \rightarrow \) 74.01 kg of CO2
- Fuel energy density of diesel = 38.6 MJ/L (Fuel energy density,[13])
- 1 L of diesel (releases) \( \rightarrow \) 38.6 MJ energy
- 1 L of diesel (releases) \( \rightarrow \) 0.0386 GJ energy \[1 GJ = 1000 MJ]\)
- 25.9 L of diesel (releases) \( \rightarrow \) 1 GJ of energy

Therefore, on equating (1) and (2)
- 25.9 L of diesel (generates) \( \rightarrow \) 74.01 kg of CO2
- 1 L of diesel (generates) \( \rightarrow \) 2.857 kg CO2

Since, the truck weighs an average of 16 tons with 4 km per liter mileage

Therefore, in 1 L, the truck travels 4 km (roughly)

Which implies that, 2.857 kg of CO2 is released when the truck travels 4 km.

That is, 0.71425 kg of CO2 is released when the truck travels 1 km.

Thus, the CO2 emission factor (in kg CO2/ km) = 0.7145

| S. No. | Transport Description | Fuel type used | Distance travelled On-site (km) (I) | CO2 emission Factor (in kg CO2/ km) (II) | Total emissions (in kg) (= I x II) |
|--------|-----------------------|----------------|------------------------------------|----------------------------------------|----------------------------------|
| 01     | Truck                 | Diesel         | 7904157584                         | 0.7145                                 | 5645544554                      |

Therefore, \(X_3' = 5.6455 \text{ MT CO}_2\)

Total CO2 emissions from scope 1 is \(X = X_1 + X_2 + X_3 = 12.5 + 8.452 + 5.645 = 26.59 \text{ MT} \approx 26.6 \text{ MT}\)

**SCOPE 2: Calculating CO2 emissions due to indirect air emissions**

Average of emission factors = .806 kg CO2/Kwh (Indian Cement tool, [6])

Total electricity consumed = 6,01,649,000Kwh (ABC Sustainability Report 2019)

Total CO2 released due to indirect air emissions = (Electricity emission factor) * (total electricity consumed)

Total emissions = (6,01,649,000) x (.806) = 484929094 kg CO2 = 0.484929094 MT CO2

Tabulated as below.

| S. No. | Description | Electricity Purchased (in kWh) (I) | CO2 emissions Factor (in g CO2/ kWh) (II) | Indirect CO2 Emissions (in kg) (= I x II) |
|--------|-------------|-----------------------------------|------------------------------------------|------------------------------------------|
Therefore, \( Y = 0.4849 \text{ MT CO}_2 \)

Total carbon dioxide emissions in ABC Industry

\[
X + Y = 26.6 + 0.4849 = 27.08 \text{ MT CO}_2
\]

ABC produces approximately 27.08 MT of CO\(_2\) emissions for a cement production of 33.05 MT. It means that 0.8195 ton of CO\(_2\) is emitted per ton of cement production.

**Limitations**

The import and export of clinker and other raw materials have not been considered. Certain assumptions like mileage of vehicle have been done well under the acceptable guidelines which may differentially alter the accuracy of the result.

**VI. RESULTS AND DISCUSSION**

The carbon footprint for the company ABC as calculated from the framework is now scope-wise tallied with the officially generated Sustainability Report 2019 of ABC as in the table below.

| Scope – wise emissions (MT CO\(_2\)) | Using customized framework | As reported in Sustainability Report of ABC |
|-------------------------------------|---------------------------|------------------------------------------|
| SCOPE 1                             | 26.6                      | 16.6                                     |
| SCOPE 2                             | 0.484929                  | 0.534401                                 |
| SCOPE 3                             | -                         | 0.675988                                 |
| Total                               | 27.08                     | 17.83                                    |

The above results indicate that for the production of 33.05 MT of cement, the CO\(_2\) emissions as calculates using the framework and that reported by the company vary. From the customized framework, it has been concluded that \((27.08/ 33.05) = 0.819 \text{ t of CO}_2\) is emitted per ton of cement production. While, it has been reported that ABC emits \((17.83/ 33.05) = 0.539 \text{ t of CO}_2\) per ton of cement production.

**VII. CONCLUSION**

The framework is factual and incorporates every aspect of GHG emissions during the whole cement manufacturing process and may therefore be used for calculating CO\(_2\) emissions of any Indian cement – producing company. During the CF analysis of ABC Company, it was found that the emissions reported were much lower then what should have been the case if proper methodology for CF analysis had been followed. Image enhancement, tax evasion and maintaining brand value might have been the motive behind the cause.
This work will also act as a guide to those who want to learn and apply this particular framework in calculating CF of Indian cement plants in future and plan the strategy to reduce the CO\(_2\) emission.

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