Manufacturing and Industrial Processes sector: Cement Manufacturing Emissions

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1. Introduction

There is one important number that encapsulates the tremendous importance of the cement industry worldwide: 7%. It describes both the global industrial energy use of the cement sector, making it the third-largest industrial energy consumer, but it also captures the fraction of global carbon dioxide (CO_2) emissions this sector is responsible for (IEA, 2018). Thus, it has the second-largest share of total direct industrial CO_2 emissions. Most emissions related to the cement industry do not originate from the large quantities of thermal energy that are provided from fossil fuels combustion but are rather due to the calcination process directly. In 2016, global process emissions from cement production were equivalent to about 4% of global emissions from fossil fuels (Andrew, 2018). Mixed with air, water, sand and gravel, cement makes concrete, the most consumed manufactured substance on the planet. Concrete builds homes, schools, hospitals, workplaces, transport systems and infrastructure for clean water, sanitation and energy, which are essential for quality of life as well as social and economic wellbeing. Due to the key role it plays in modern society, cement demand is expected to grow by 12-23% by 2050 from 2018 levels (IEA, 2018). Almost three quarters of the global cement production originates from only two countries: China accounts for almost 60% and India is responsible for 16% (IEA, 2018).

Cement production can be used as a proxy for emissions and therefore it is desirable to estimate facility level production to track changes in emissions and guide climate policy. With any such globally traded commodity, however, it is characterised by fierce competition amongst producers and, consequently, facility level production data is rarely made publicly available. In most cases it is only possible to obtain steel production at the country level (USGS, 2024; NBSC, 2024) but often there is a substantial delay (~years) in obtaining the data. EU and U.S. plant level emissions data can be sourced from respective registers (E-PRTR, 2024; US EPA, 2024).

In this work, we address both the temporal and spatial limitations in traditional cement emissions reporting to provide more timely facility level estimates. More specifically, we have aimed to deliver cement emissions based on production estimates on a monthly basis for all assets identified on the Spatial Finance Initiative database (McCarten *et al.*, 2021). We have achieved this by primarily using satellite-derived hotspot data which can capture variation in activity for most clinker-producing cement facilities.

2. Materials and Methods

To produce cement, direct emissions are released during the manufacturing of clinker, not only because of the CO_2 generated in the calcination process, but also due to the combustion of fossil fuels which provides most of thermal energy. More information on cement production is provided in section 7.1 and highlighted in Figure 5.

Given the lack of asset-level emission data publicly available, a standardised "bottom-up" approach is used to quantify the emissions. This process is characterised by first estimating production levels for each plant before applying an emission factor to generate emissions estimates.

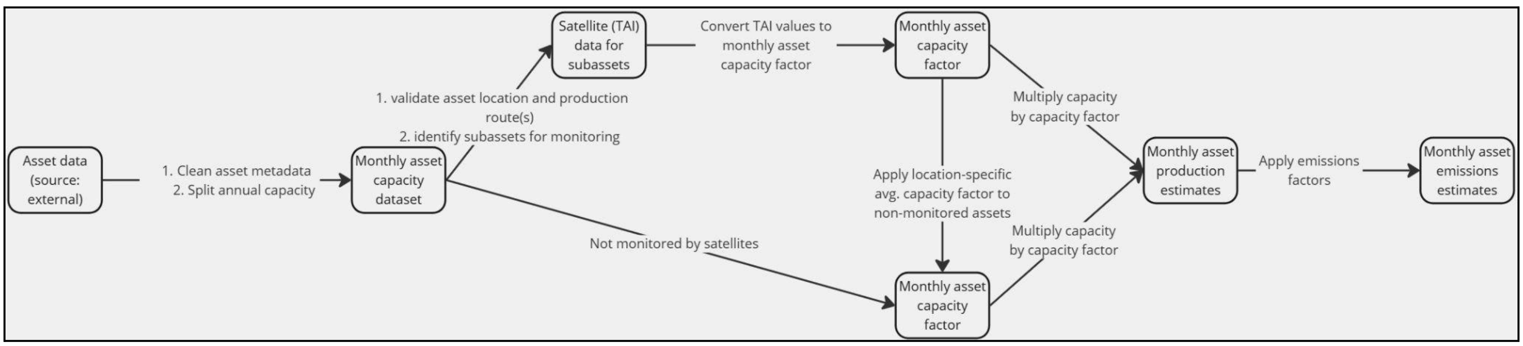


Figure 1 Flowchart of the methodology to calculate plant level emissions for global cement assets.

2.1. Materials

2.1.1. Asset inventory dataset

Cement production consists of three steps: first limestone is mixed with other materials, then the mixture is heated up to produce clinker, and finally this clinker is grinded together with other ingredients to produce cement. The final grinding process can happen in so-called integrated facilities where the clinker is also produced or in independent grinding facilities closer to its end market. Spatial Finance Initiative provided facility level information such as GPS coordinates, owner, capacity, age, product and technology type (McCarten *et al.*, 2021).

The database includes both integrated and grinding plant types. In this work, we estimate emissions for only clinker-producing assets, therefore we only keep integrated plants. In total there are 2,241 integrated cement plants across 138 countries. We manually validated the locations of all the plants using geolocation data from Google Maps API (Google Maps, 2024) and OpenStreetMap (OpenStreetMap, 2024).

Figure 2 shows how integrated cement plants are distributed globally with high concentration of assets in China which produces more than half of the global production, followed by India at 16%. The map also highlights countries with little to no cement production.

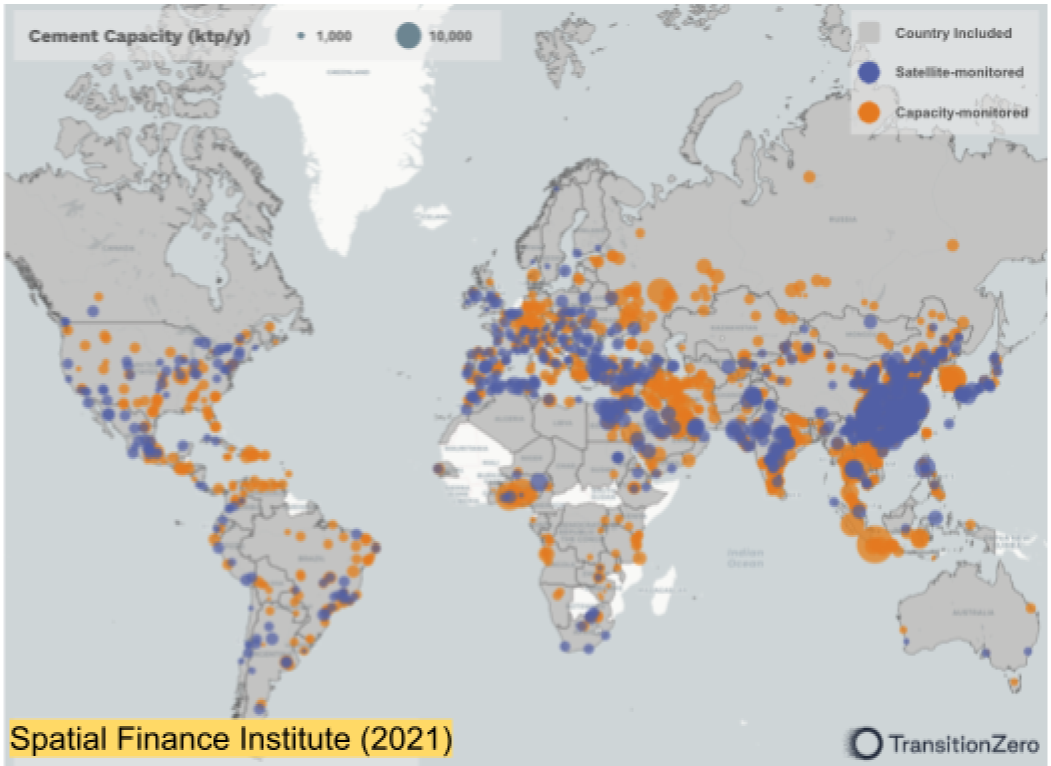


Figure 2 Global map showing integrated cement facilities. Countries included in cement emissions monitoring are shaded. Assets that are monitored with satellites are shown in blue, whereas as the rest are shown in orange. Source: McCarten *et al.* (2021).

2.1.2. Remote sensing datasets

Satellite-derived production estimates make use of multispectral imagery from two different collections:

- The European Space Agency (ESA) Copernicus Sentinel mission with a resolution of 20 m and a combined 5-day equator revisit with two satellites:
    - Sentinel 2A: with imagery available since 2015 (ESA, 2024).
    - Sentinel 2B: with imagery available since 2017 (ESA, 2024).

  Both Sentinel-2 satellites have a MultiSpectral Instrument (MSI) that can measure wavelengths from ~443 - ~2190 nm (blue to shortwave infrared (SWIR)) at 10-60 m spatial resolutions.

- The U.S. Geological Survey (USGS) and National Aeronautics and Space Administration (NASA) Landsat program with a resolution of 30 m and a combined 8-day revisit:
    - Landsat-8: with imagery available since 2013 (NASA and USGS, 2024a).

  - Landsat-9: with historical images available from 2021 (NASA and USGS, 2024b).

Both Landsat-8 and Landsat-9 have an Operational Land Imager (OLI) that can measure wavelengths from ~435 - ~1384 nm (blue to thermal infrared) at 15-100 m spatial resolutions.

All satellite datasets were sourced and processed using Google Earth Engine (Google Earth Engine, 2024a, 2024b, 2024c). From each satellite dataset, we relied on the surface reflectance products and computed the ratio of the difference between two SWIR bands and NIR bands of each satellite. This is based on the study to detect high-temperature anomalies from Sentinel-2 MSI images where a tri-spectral thermal anomaly index (TAI) that jointly uses the two high-temperature sensitive SWIR bands and the high-temperature-insensitive NIR band to enhance High Temperature Anomalies (Yongxue et al., 2021). For the respective satellite collections, we infer the TAI through the following equations:

- Sentinel-2A/B: $TAI = \frac{(B12 - B11)}{(B8a)}$

- Landsat-8/9: $TAI = \frac{(B7 - B6)}{(B5)}$

Figure 3 Left - high resolution image of Lafarge's cement plant in Port-la-nouvelle, France with a manually labelled rotary kiln (yellow shaded rectangle). Right - Sentinel-2 image which shows the thermal anomaly over the rotary kiln and surrounding features (red for hot pixel) during 2023. Source: Modified Copernicus data and SFI dataset

Where B# refers to the band number for the specific satellite. This ratio was used to identify thermal anomalies within the temperature range of industrial processes, while eliminating most of the noise from reflectance interference. Pixel values between the Sentinel 2A/B MSI and Landsat OLI were harmonised using NASA's band pass adjustments allowing the two image collections to be used as if they were a single collection (NASA, 2018). The harmonised dataset ensured higher revisit for time-series surface applications. Partial images (coverage of the steel facility's boundaries less than 80%) and cloudy images (more than 20% clouds) were excluded. Figure 3 shows an example of a cement plant with identified hotspots over a rotary kiln.

2.1.3. Production datasets

Aggregated national cement production used in our models is primarily sourced from USGS (2024) on an annual basis.

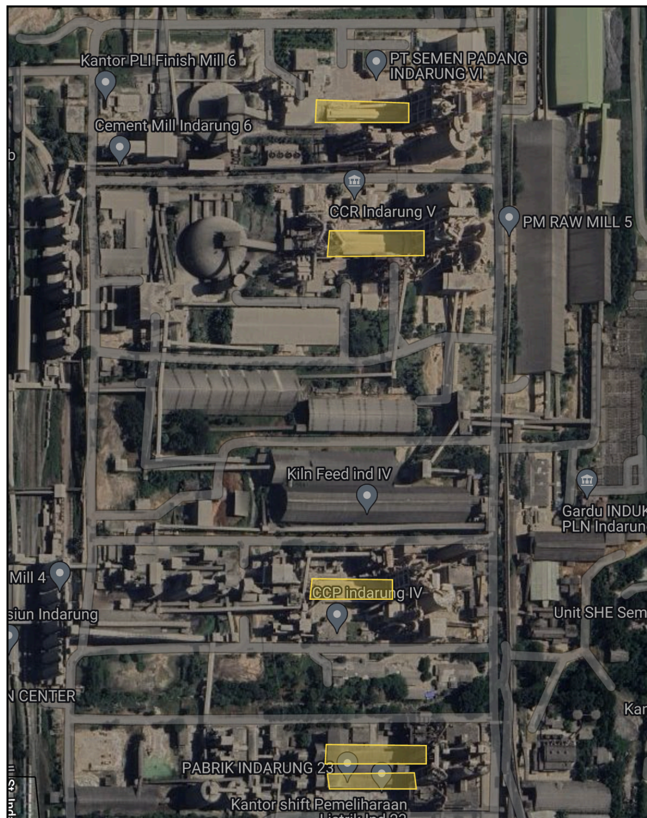
2.1.4. Emissions factors dataset

A global emissions factor was used for process, fuel and indirect emissions from electricity use and sourced from IEA (2018).

2.2. Methods

2.2.1. Production methodology

Two approaches were used to estimate asset level production. As a priority, satellite-derived production estimates are used whenever a facility releases enough heat to be captured by satellite imagery (Zhou *et al.*, 2018; Marchese *et al.*, 2019; Liangrocapart, Khetkeeree and Petchthaweetham, 2020). This is the case for clinker-producing plants as clinkerization occurs at high temperatures of around 1,400ºC.



kilns have been hand labelled (yellow shaded rectangles).

Our methodology scours satellite imagery for heat signatures from the operating cement plants. Each clinker, once identified, is outlined with a hand-drawn polygon, as shown in Figure 4.

The intensity of the hotspot above each clinker is calibrated against the annual country level production data (USGS , 2024) to estimate plant activity in each month.

For plants where no suitable hotspot signals were found, we extrapolated the regional or global average of satellite derived utilisation rates if we monitored other facilities in the same country or not.

Even though the satellite-based approach better represents the fluctuations in plant activity, such as capturing if a plant has been switched off. There are several reasons why activity of some assets cannot reliably be estimated using this method. Most often, assets are excluded from satellite monitoring due to a small signal-to-noise ratio which makes it difficult to distinguish between production and background fluctuations. Other sources of complication can be the occasional presence of strong reflections from a-priori cold elements, or the fact that kilns may be placed inside a building and hidden by a roof. A representative example is shown in Section 7.2 Figure 6.

2.2.2. Emissions methodology

We model emissions by multiplying cement production estimates by emission factors including different types of emissions. We detail in this section the different emissions factors considered and their corresponding source. Two types of emissions are accounted for here: direct and indirect emissions. Direct emissions were split into process emissions and fuel emissions. Fuel emissions were further split into kiln fuel and non-kiln fuel emissions.

Table 1 Emission types and associated emissions factor

<table>
<tr><td rowspan="5">Type of emissions</td><td colspan="3">Direct emissions</td><td>Indirect emissions</td></tr>
<tr><td>Process emissions</td><td colspan="2">Fuel emissions</td><td rowspan="3">External power consumption from the national grid</td></tr>
<tr><td rowspan="2">Limestone calcination
$CaCO_3 \rightarrow CaCO + CO_2$
Cement kiln dust</td><td>Kiln fuel emissions</td><td>Non-kiln fuel emissions</td></tr>
<tr><td>Heat consumption of kilns
Drying of fuels
Drying of raw materials</td><td>On-site power generation</td></tr>
<tr><td>0.32 t-CO2/t-cement</td><td colspan="2">0.2 t-CO2/t-cement</td><td>0.091</td></tr>
<tr><td>Source</td><td>IEA (2018)</td><td colspan="2">IEA (2018)</td><td>IEA (2018) and Ember (2024)</td></tr>
</table>

2.3. Coverage

Based on 2023 emission numbers, asset level estimates account for 68% (1.51 Gt) of sectors direct emissions. Satellite-monitored assets represented 93% of the total integrated assets and contributed to 93% of the total asset level emissions estimates.

3. Results and analysis

Figure 5 illustrates the relationship between satellite-derived Thermal Anomaly Index (TAI) and the corresponding emissions for a cement plant in Spain. The data demonstrates that, for most months, estimated emissions (based on production levels) align closely with fluctuations in TAI. For example, both measurements increase prior to after July 2021 and then rapidly increase between July 2021 and Jan 2022, after which both decrease into January 2022. However, further calibration is needed to enhance the model that translates TAI into asset-level production estimates, as TAI data can vary significantly by asset depending on factors like equipment type, age, geographic location, and other operational conditions. The TAI values presented here are derived from the hotspot data shown in Figure 6.

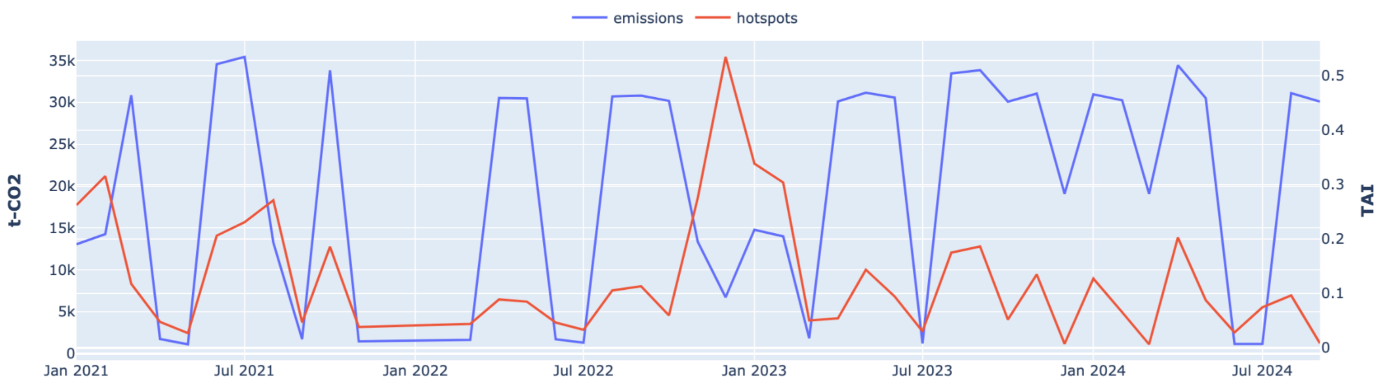


Figure 5 Satellite-based Thermal Anomaly Index (TAI; red solid line) and estimated emissions (blue solid line) at Valderrivas cement plant in Cantabria, Spain during January 2021 - September 2024.

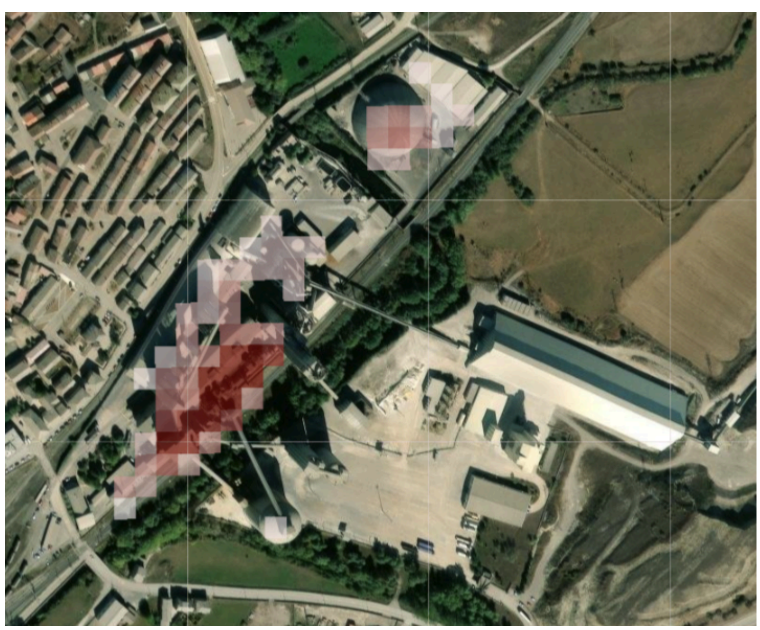


Figure 6 Satellite-detected hotspots over Valderrivas cement plant in Cantabria, Spain during August 2024.

Tables 2 and 3 show the biggest producers and emitters in the cement sector at country and plant level, respectively. As was described in the Climate TRACE methodology, "*Iron & Steel Manufacturing Emissions*", China accounts for more than half of the global cement production and emissions and 9 of the 10 most emitting cement plants are located in China (Table 3).

Table 2 Top 10 emitters in the cement industry in 2023 - by country

Country	CO_2 Emissions ($MtCO_2$)
China	1,150
India	205
Vietnam	64
USA	49
Turkey	40
Indonesia	35
Brazil	34
Russia	33
Iran	32
Japan	29

Table 3 Top 10 emitters in the cement industry in 2023 - by plant

Plant name	Country	Capacity (Mt)	CO_2 emissions ($MtCO_2$)
Guangxi Zhuangzuzizhiqu 7	China	30	12.1
Liaoning Sheng 11	China	30	9.9
Hubei Sheng 13	China	22	8.3
Shandong Sheng 11	China	25	6.9
Hebei Sheng 8	China	20	6.5
Hebei Sheng 6	China	20	6.1
Sichuan Sheng 45	China	18	5.8
Shanxi Sheng 6	China	20	5.8
Jiangxi Sheng 11	China	20	5.5
Nuvoco Vistas Corporation Ltd Rajasthan 2	India	13.5	5.4

4. Conclusions and Discussions

In this work a new approach has been implemented to estimate cement production and emissions estimates at a facility level for 2241 integrated cement facilities, covering 138 countries, in the SFI database.

Our cement emissions estimates modelling approach consists of first, estimating facility level production, and second, applying a relevant emissions factor to yield facility emissions. The approach for estimating cement production at the facility level is dependent upon availability of data.

The cement production for each plant was estimated using a hybrid approach. Where possible, satellite-based estimates TAI measurements from each facility against national cement production numbers. For facilities where no suitable hotspot signals could be extracted, we extrapolated the regional utilisation rates derived from satellite data to infer production estimates. Based on the 2023 numbers, our satellite-monitored assets contributed 64% of the total emissions.

Electricity related emissions estimated in this work include emissions originating from the grinding process, which may or may not occur in the same facility where the clinker was produced. The SFI database contains 842 grinding assets (where no clinker is produced) that contribute to 23% of global cement capacity but are not included in the present work. Power-related grinding emissions are treated as if they were occurring in the facility that produced the clinker. This assumption allows us to cover a broader scope of emissions but does not create a large bias on the asset-level estimates since the grinding emissions contribute less than 5% of the total emissions (Shen *et al.*, 2014).

Ultimately, this work has shown that timely facility level production and emissions can be obtained without the need to rely upon systematic and exhaustive factory published figures, often years out of date. Additionally, this work may open pathways to assist in future climate policy. Future work may benefit from greater availability of asset data for model training. An additional source of improvement would be the inclusion of grinding plants from the SFI database to correctly distribute cement grinding emissions, but this requires the knowledge of clinker flows between plants which has not been investigated in the scope of this work. Lastly, discussed in section 7.2, removing thermal (TAI) measurements not related to cement production but can occur due to other activities and features at a cement plant.

5. Supplementary metadata section

Cement sector CO_2 emissions are reported for individual assets from January 2021. The emissions described here represent a subset of specific country-level emissions estimates from the Climate TRACE manufacturing sector. All data is freely available on the Climate TRACE website (https://climatetrace.org/). A detailed description of what is available is described in Tables 4 - 6.

Table 4 Details on the asset metadata

General Description	Definition
Sector definition	*Emissions from cement production*
UNFCCC sector equivalent	*2.A.1 Cement production*
Temporal Coverage	*2021 - present*
Temporal Resolution	*Monthly*
Data format	*CSV*
Coordinate Reference System	*None. ISO3 country code provided*
Number of emitters available for download	*2,241 integrated cement plants covering 138 countries*
What emission factors were used?	*Process specific global average emission factors*
What is the difference between a "0" versus "NULL/none/nan" data field?	*"0" values are for true non-existent emissions. If we know that the sector has emissions for that specific gas, but the gas was not modelled, this is represented by "NULL/none/nan"*
total_CO2e_100yrGWP and total_CO2e_20yrGWP conversions	*Climate TRACE uses IPCC AR6 CO_2e GWPs. CO_2e conversion guidelines are here: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_FullReport_small.pdf*

Table 5 Definition of the fields in asset dataset

Data attribute	Definition
sector	manufacturing
source_sub-sector_name	cement
source definition	emissions from cement production
start_date	start date for time period of emissions estimation (YYYY-MM-DD format)
end_date	end date for time period of emissions estimation (YYYY-MM-DD format)
asset_identifier	internal identifier
asset_name	name of the facility
iso3_country	ISO 3166-1 alpha-3 country code
location	well-known text (WKT) point location
type	manufacturing method

Data attribute	Definition
capacity	monthly plant capacity
capacity_factor	utilisation rate of cement plants
activity	production estimates
CO2_emissions_factor	direct emissions factor (t-CO_2/t-cement)
CH4_emissions_factor	not used; N/A
N2O_emissions_factor	not used; N/A
CO2_emissions	direct emissions estimates (t-CO_2)
CH4_emissions	not used; N/A
N2O_emissions	not used; N/A
total_CO2e_100yrGWP	100 years global warming potential (t-CO_2e)
total_CO2e_20yrGWP	20 years global warming potential (t-CO_2e)
other1	direct and indirect emissions factor, includes - calcination, fuel use and electricity use (t-CO_2/t-cement)
other2	direct and indirect emissions (t-CO_2)
other3	calcination emissions factor (t-CO_2/t-cement)
other4	calcination emissions (t-CO_2)
other5	fuel emissions factor (t-CO_2/t-cement)
other6	fuel emissions (t-CO_2)
other7	electricity use factor (MWh/t-cement)
other8	electricity use (MWh)
other9	grid emissions intensity (t-CO_2/MWh)
other10	model_methodology (e.g. satellite_monitored or extrapolation)
model_number	version of the model (e.g. 1, 2, …)

Table 6 Definition for confidence and uncertainty in asset data.

Data attribute	Confidence Definition	Uncertainty Definition
type	● *Very low:* Based on highly speculative or obsolete information. Very low level of confidence in the accuracy of asset classification.	Not used; N/A

Data attribute	Confidence Definition	Uncertainty Definition
	● *Low:* Limited or somewhat outdated data. Low level of confidence in the classification's correctness. ● *Medium:* A mix of historical and more recent data. A medium level of confidence in its accuracy. ● *High:* Grounded in comprehensive and recent data. A high level of confidence in the precise classification of the asset. ● *Very high:* Extensive, up-to-date, and verified data. A very high level of confidence in the accurate and detailed identification of the asset.	
capacity	● *Very low:* Limited or outdated data, and significant uncertainties exist. ● *Low:* Outdated and/or incomplete data. ● *Medium:* A mix of historical and recent data. ● *High:* Comprehensive and recent data updates. High level of certainty. ● *Very high:* Extensive, up-to-date, and verified data. A very high level of certainty.	Not used; N/A
capacity_factor	● *Very low:* Data is sparse or highly unreliable. Considerable uncertainty in capacity factor estimations. ● *Low:* Moderate uncertainty in capacity factor calculations. ● *Medium:* Data is sufficiently available, though not comprehensive. No absolute accuracy in capacity factor estimations. ● *High:* High confidence in the accuracy of capacity factor calculations. ● *Very high:* Derived from thorough and validated data sources. Very high precision of capacity factor estimations.	Not used; N/A
activity	● *Very low:* Largely speculative or based on outdated information. A very low level of confidence in activity assessments. ● *Low:* Limited or somewhat outdated sources. A low level of confidence in the activity assessments. ● *Medium:* A mix of historical and more recent data. Medium level of confidence in activity insights. ● *High:* Detailed and current operational data ensures a high level of confidence in the accuracy of activity assessments. ● *Very high:* Extensive, verified, and up-to-date data. A very high level of confidence in their accuracy.	±10% of asset production (based on IPCC)
CO2_emissions_factor	● *Very low:* Highly uncertain due to insufficient or unreliable data. ● *Low:* Estimated from incomplete data. Low confidence level in its precision. ● *Medium:* A mix of historical and more recent data. Medium level of confidence in their accuracy.	±10% of asset (based on IPCC)

Data attribute	Confidence Definition	Uncertainty Definition
	• *High:* Derived from comprehensive and recent data. A high level of confidence in their precision. • *Very high:* Based on extensive and validated data, providing a very high level of confidence in their precision.	
CH4_emissions_factor	Not used; N/A	Not used; N/A
N2O_emissions_factor	Not used; N/A	Not used; N/A
CO2_emissions	• *Very low:* Based on very rough estimations or outdated information. A very low level of confidence in its accuracy. • *Low:* Estimated from incomplete data. Low confidence level in its precision. • *Medium:* A mix of historical and more recent data. Medium level of confidence in their accuracy. • *High:* Derived from comprehensive and recent data. A high level of confidence in their precision. • *Very high:* Based on extensive and validated data, providing a very high level of confidence in their precision.	±20% of asset emissions
CH4_emissions	Not used; N/A	Not used; N/A
N2O_emissions	Not used; N/A	Not used; N/A
total_CO2e_100yrGWP	• *Very low:* Based on very rough estimations or outdated information. A very low level of confidence in its accuracy. • *Low:* Estimated from incomplete data. Low confidence level in its precision. • *Medium:* A mix of historical and more recent data. Medium level of confidence in their accuracy. • *High:* Derived from comprehensive and recent data. A high level of confidence in their precision. • *Very high:* Based on extensive and validated data, providing a very high level of confidence in their precision.	±20% of asset emissions
total_CO2e_20yrGWP	• *Very low:* Based on very rough estimations or outdated information. A very low level of confidence in its accuracy. • *Low:* Estimated from incomplete data. Low confidence level in its precision. • *Medium:* A mix of historical and more recent data. Medium level of confidence in their accuracy. • *High:* Derived from comprehensive and recent data. A high level of confidence in their precision.	±20% of asset emissions

Data attribute	Confidence Definition	Uncertainty Definition
	• *Very high:* Based on extensive and validated data, providing a very high level of confidence in their precision.	

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Disclaimer: The emissions provided for this sector are our current best estimates of emissions, and we are committed to continually increasing the accuracy of the models on all levels. Please review our terms of use and the sector-specific methodology documentation before using the data. If you identify an error or would like to participate in our data validation process, please contact us.

6. References

1. Andrew, R.M. (2018) '*Global CO2 emissions from cement production*', Earth System Science Data, 10(1), pp. 195–217. Available at: https://doi.org/10.5194/essd-11-1675-2019
2. Construction Cost (2016) *Cement Production Process*, *Cement Production Process*. Available at: https://www.constructioncost.co/cement-production-process.html
3. Ember (2024) '*Regional grid intensity retrieved from: Monthly Electricity Data',* Ember. Available at: https://ember-energy.org/data/monthly-electricity-data/
4. E-PRTR (2024) '*Cement emissions data retrieved from: E-PRTR*', European Pollutant Release and Transfer Register. Available at: http://prtr.ec.europa.eu/
5. ESA (2024) '*Satellite images data retrieved from: Copernicus Sentinel-2 ESA*', European Space Agency Available at: https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-2
6. Google Earth Engine (2024a) *Landsat 8 Datasets in Earth Engine*, *Google Developers*. Available at: https://developers.google.com/earth-engine/datasets/catalog/landsat-8 .
7. Google Earth Engine (2024b) *Landsat 9 Datasets in Earth Engine*, *Google Developers*. Available at: https://developers.google.com/earth-engine/datasets/catalog/landsat-9 .
8. Google Earth Engine (2024c) *Sentinel-2 Datasets in Earth Engine*, *Google Developers*. Available at: https://developers.google.com/earth-engine/datasets/catalog/sentinel-2.
9. Google Maps (2024) 'Cement inventory data retrieved from: Google Maps', Google. Available at: https://www.google.co.uk/maps .
10. IEA (2018) '*Technology Roadmap - Low-Carbon Transition in the Cement Industry*',

International Energy Agency, p. 66.
11. Liangrocapart, S., Khetkeeree, S. and Petchthaweetham, B. (2020) '*Thermal Anomaly Level Algorithm for Active Fire Mapping by Means of Sentinel-2 Data*', in 17th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), pp. 687–690. Available at: https://doi.org/10.1109/ECTI-CON49241.2020.9158262 .
12. Marchese, F. *et al.* (2019) '*A Multi-Channel Algorithm for Mapping Volcanic Thermal Anomalies by Means of Sentinel-2 MSI and Landsat-8 OLI Data*', Remote Sensing, 11(23), p. 2876. Available at: https://doi.org/10.3390/rs11232876.
13. NASA (2018) 'Band Pass Adjustment', National Aeronautics and Space Administration Available at: https://hls.gsfc.nasa.gov/algorithms/bandpass-adjustment/.
14. NASA and USGS (2024a) '*Satellite images data retrieved from: Landsat-8 NASA/USGS*', National Aeronautics and Space Administration and United States Geological Survey. Available at: https://www.usgs.gov/landsat-missions/landsat-8.
15. NASA and USGS (2024b) '*Satellite images data retrieved from: Landsat-9 NASA/USGS*', National Aeronautics and Space Administration and United States Geological Survey. Available at: https://www.usgs.gov/landsat-missions/landsat-9.
16. NBSC (2024) '*Chinese steel production data retrieved from: NBSC*', National Bureau of Statistics of China. Available at: http://www.stats.gov.cn/english/
17. OpenStreetMap (2024) '*Cement inventory data retrieved from: OpenStreetMap*'. OpenStreetMap. Available at: https://www.openstreetmap.org .
18. McCarten, M., Bayaraa, M., Caldecott, B., Christiaen, C., Foster, P., Hickey, C., Kampmann, D., Layman, C., Rossi, C., Scott, K., Tang, K., Tkachenko, N., and Yoken, D. (2021). *Global Database of Iron and Steel Production Assets*, Spatial Finance Initiative. Available at: https://www.cgfi.ac.uk/spatial-finance-initiative/geoasset-project/geoasset-databases/
19. Shen, L. *et al.* (2014) '*Factory-level measurements on CO2 emission factors of cement production in China*', Renewable and Sustainable Energy Reviews, 34, pp. 337–349. Available at: https://doi.org/10.1016/j.rser.2014.03.025.
20. US EPA (2024) '*Cement emissions data retrieved from: US EPA*', United States Environmental Protection Agency. Available at: https://www.epa.gov/.
21. USGS (2024) '*Cement production data retrieved from: USGS Cement Statistics and Information*', United States Geological Survey. Available at: https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information
22. Yongxue, L., Weifeng, Z., Bihua, X., Wenxuan, X., Wei, W. (2021) '*Detecting high-temperature anomalies from Sentinel-2 MSI images*', ISPRS Journal of Photogrammetry and Remote Sensing, 177, p. 174-193, Available at: https://doi.org/10.1016/j.isprsjprs.2021.05.00
23. Zhou, Y. *et al.* (2018) '*A Method for Monitoring Iron and Steel Factory Economic Activity Based on Satellites*', Sustainability, 10(6), p. 1935. Available at: https://doi.org/10.3390/su10061935.

7. Appendices

7.1. Overview of the cement production process

The cement production process starts with mining and quarrying, where raw materials are extracted from the environment. Then, three main operations are performed. First, raw meals made of an appropriate mix of crushed limestone, calcium, silicon, aluminium and iron oxides are prepared. Second, raw meals are placed into a kiln where a large flame elevates the temperature greatly to allow for formation of clinker by chemical reaction and thereby releasing CO_2. The thermal energy provided by the kiln originates from the combustion of various types of fuels ranging from traditional fossil fuels like coal and oil to alternative waste fuels and biomass. Third, cooled clinkers are ground and mixed with gypsum to create cement. An overview of this process is highlighted in Figure 7.

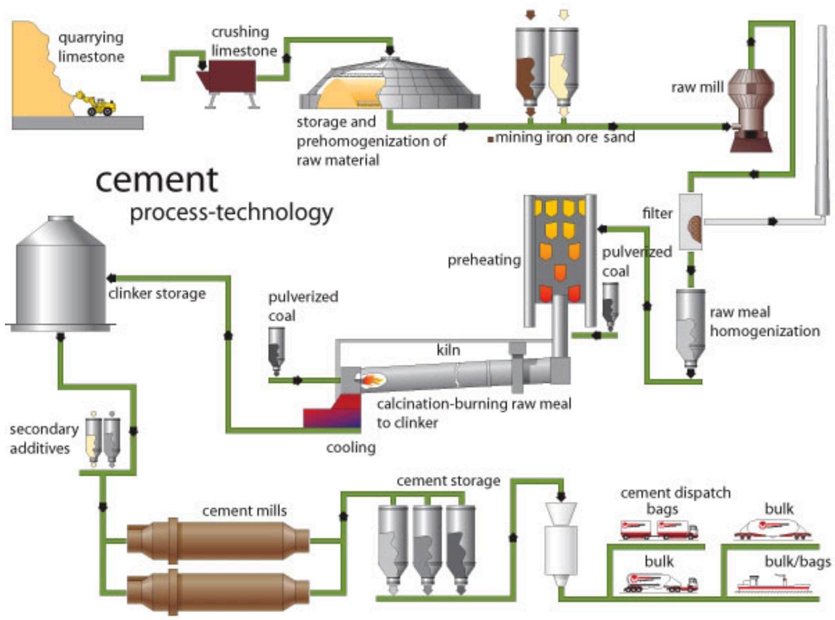

Figure 7 Overview of the cement production process (Construction Cost, 2016).

7.2. Limits to hotspot mapping

Figure 8 depicts an example of a cement plant that is not monitored with satellite due to small signal-to-noise ratio limitations. Not only the heat signal is much more diluted around the kiln in comparison to the plant of Figure 3, but we also observe undesired signals originating from reflections on the coal stack.

Figure 8 Left - High resolution image of the Stockertown cement plant in Pennsylvania, United States. Right - composite Sentinel-2 image of the same plant. Heat signals (red areas) are not situated over kiln areas but on the coal stack (dashed circles). Sources: modified Copernicus and USGS data.