

KEY MESSAGES

- The decarbonisation of heavy industry is key to achieving deep cuts in emissions in line with the Paris Agreement's long-term temperature goal.
- Reducing these industrial emissions is challenging, as heavy industry emissions are often intrinsically linked to the production process.
- Improvements in efficiency and decarbonisation of the energy supply can lead to emissions reductions. Their combined potential for both steel and cement is estimated to be around a 30%–50% reduction below current trends by 2050.
- To further decarbonise heavy industry sectors, a shift to innovative low-carbon technologies, product substitutions, circular production routes, and possible industrial scale deployment of CCS will be needed. Targeted RD&D efforts are necessary to accelerate the availability of these options.

INTRODUCTION

To limit global warming to 1.5°C by the end of the century, emissions from energy supply and industry will need to reach net zero by around 2050 (Rogelj et al. 2015).

While energy systems can be decarbonised through a shift to renewable sources, industry is more challenging: in many industries, CO₂ emissions originate not only from fuel combustion to generate heat or electricity, but also from fuel combustion needed to start certain chemical reactions (e.g. reduction of iron in a blast furnace), or from the chemical reactions that take place during the industrial processes (e.g. calcination of limestone during cement production).

A near-complete decarbonisation of global heavy industry is therefore not only about improving efficiency and shifting to clean fuels. It also requires more holistic thinking about wide-reaching changes to industrial sub-sectors. For example, the circular economy concept involves moving away from linear to circular value chains and from "Take, Make, Waste" to "Reduce, Reuse, Replace, Recycle." This will decrease demand for industrial products and replace high-carbon products with low-carbon

alternatives (Circle Economy & Ecofys 2016). This memo showcases future emissions pathways in two carbon intensive industries—cement and steel—under different scenarios (see Annex A for modelling details) to highlight the opportunities and challenges for emission reductions.

We analyse three scenarios for each sector: one following **current trends**, one representing a shift towards **decarbonisation** of the energy supply, and one representing further **steps towards circular economy**-based value chains. We also highlight the extent by which other step-change technologies can "close the gap" to net-zero emissions.

STEEL SECTOR: TRENDS

The global steel sector has grown considerably over recent decades. As shown in Figure 1, this growth can be predominantly attributed to the rapid expansion of China's steel sector. The consequence of this growth in production has resulted in significant increases in global steel-related CO₂ emissions, from 1.3 Gt to 2.8 Gt over 1990–2015 (IEA 2016c), or about 5% of global GHG emissions in 2012 (JRC & PBL 2014).

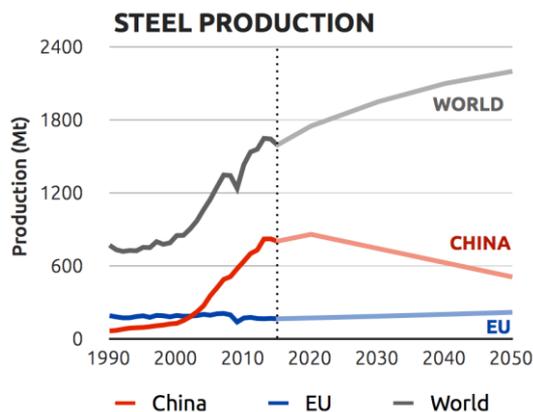


Figure 1: Steel production worldwide and in China and the EU. Historical data 1990–2015 and projections in China and the EU up to 2050. Data sources are listed in Annex B.

Trends in steel production can be partially explained by the 'intensity of use curve' hypothesis which links material consumption per GDP with GDP per capita (World Steel Association 2016b). As economies grow, material use per unit of GDP expands, followed by a per capita stabilisation or decrease once an economy has attained a typical GDP per capita level. Following this point, steel demand will be more strongly influenced by the rate at which existing infrastructure is replaced in the future

and the trajectory of steel demand from other applications such as cars.

Closely connected to this trend are steel recycling volumes. More scrap will become available in the future as increasing volumes of infrastructure and cars reach the end of their lifetime. The processed volumes of scrap in 2050 are expected to be three times that of today (Pauliuk et al. 2013), enabling the manufacture of more secondary steel.

Steel-related CO₂ emissions differ, depending on the production route used. There are two main manufacturing routes: the blast furnace-basic oxygen furnace (BF-BOF) route and the electric arc furnace (EAF) route.

Currently, the BF-BOF route is the dominant process, responsible for roughly 70% of steel production (World Steel Association 2015). This process mainly uses raw materials such as coal, iron ore and limestone. The raw material is converted to pig iron in the BF and subsequently made into steel in the BOF.

The EAF route uses electricity to manufacture steel from predominantly scrap metal feedstock. Currently steel manufacturing using the EAF route represents close to a third of global steel production (World Steel Association 2016b).

There is a substantial difference between the final energy intensity of these routes—the intensity of the EAF route is one-third of that of the BF-BOF route (WWF & Ecofys 2011). Of this intensity, about 95% comes from direct energy consumption (the use of primary energy in the production process without prior conversion or transformation) in the BF-BOF route, compared to about 50% for the EAF route (see Annex B).

STEEL SECTOR: SCENARIOS

To analyse how these steel demand and production route dynamics affect steel sector emissions, we explore three scenarios:

- **Scenario A** is a **current trends** scenario that illustrates the effect of demand changes on the emissions trajectory, with incremental efficiency improvements and growth rates of EAF steel production.
- **Scenario B** is a **decarbonisation** scenario that evaluates the impact of the same demand changes as the Scenario A, coupled with decarbonisation of electricity production. This scenario also assumes that the direct energy intensity and electricity intensity of steel production of the BF-BOF and EAF routes are equivalent to estimates of the technical minimum intensities (WWF & Ecofys 2011).
- **Scenario C** is a scenario with **steps towards circularity** that takes Scenario B a step

further, with a maximum shift towards EAF steel production that takes into account scrap availability constraints. Such constraints exist despite the increase in scrap availability, as overall demand for steel grows more rapidly.

Given the constraint of scrap availability, R&D programmes on innovative primary steel production routes such as the Ultra-Low Carbon Dioxide Steelmaking (ULCOS) programme should be intensified to fasten the transition to a fully decarbonised iron and steel sector.

Carbon capture and storage (CCS) technology could play a role in decarbonising this sector; the integration of CCS with novel steel production routes is being investigated by ULCOS (ULCOS n.d.), among others. Options for zero carbon primary steel production are the combination of renewable energy with an electrolysis reduction process route, also being developed under ULCOS (ULCOS n.d.) and the production of primary steel through direct reduction of iron ore with renewables-based hydrogen (Otto et al. 2017; Weigel et al. 2016). The impact of these new routes is not captured in our scenarios due to uncertainties on their deployment rates, though they could potentially be used at industrial scale before 2050.

In our analysis, we studied two structurally different regions: the EU and China, where there are considerable differences between these two regions in terms of production route shares. For example, in 2015, China produced 6% of its steel via the EAF route and the remaining 94% via the BF-BOF route, whereas for the EU this was 39% vs. 61%. The low EAF share in China is mainly the result of limited scrap availability (Zhang et al. 2016). The EAF share is assumed to grow to 30% by 2050 in China and 44% in the EU, for Scenario A and B (Ecofys 2015; Zhang et al. 2016). In Scenario C, the EAF share is at maximum levels considering the constraint of limited scrap availability; it is assumed to increase further to 45% in 2050 for China and 53% for the EU, (Allwood & Cullen 2012; Zhang et al. 2016).

Another difference between the EU and China is the trend in steel demand. As illustrated in Figure 1 in the EU, production peaked in 2007 at 210 Mt and has since decreased by 21% in 2015 (World Steel Association 2016b). Steel production is projected to grow at the modest rate of 0.8% per year to 2050 (Boston Consulting Group & Steel Institute VDEh 2013). Developments in China are very different—steel demand more than doubled from 2005 to 2015, and steel production is expected to reach its peak around 2020, partly due to slowing GDP growth rates (Zhang et al. 2016).

The emissions trends from these scenarios are displayed in Figure 2. In Scenario A, between 2015 and 2050 emissions from the sector fall by 12% in the EU and 66% in China. The key drivers for this are the strongly different trends in steel production, as shown in Figure 1. By 2050, emissions in Scenario B compared with Scenario A are 24% lower in the EU and 40% lower in China. However, in **cumulative** terms, i.e. considering the sum of emissions in 2016 to 2050, this difference is 6% for the EU and 10% for China. Under Scenario C, emissions are further reduced; by 2050, steel sector emissions in the EU and China are 34% and 51% lower than Scenario 1. Cumulatively, this translates to reductions of 8% and 14%.

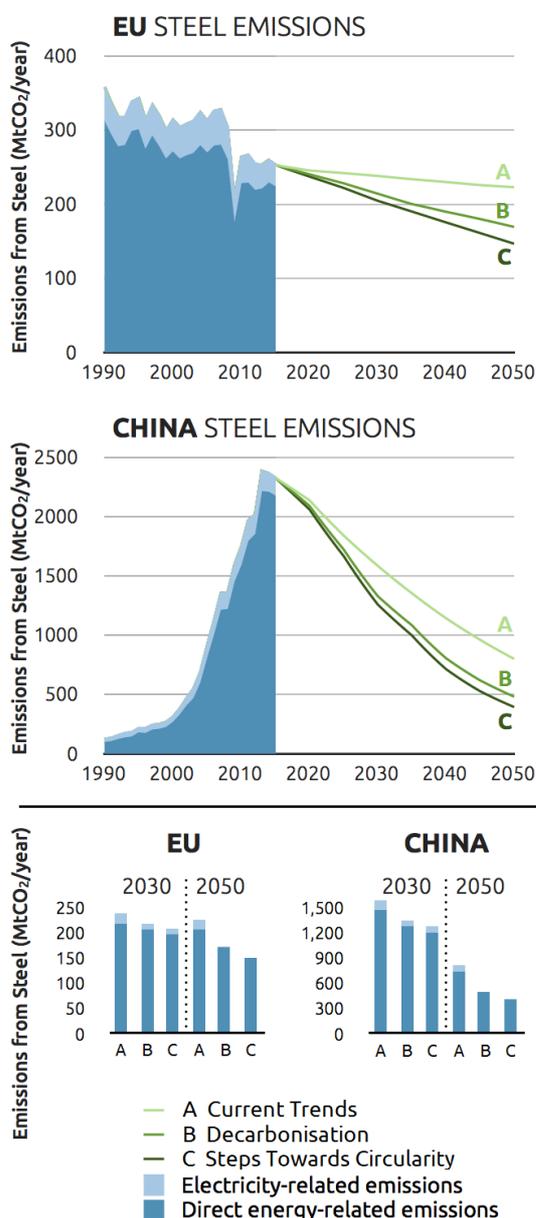


Figure 2: (Top) Emissions from steelmaking in the EU and China, historically (1990–2015) and in the future (2016–2050) under the scenarios as detailed above. Data sources and assumptions used to construct the scenarios are given in Annex B. (Bottom) The split between direct energy-related and electricity-related emissions in 2030 and 2050 under the three scenarios.

Scenario A for China demonstrates that large emission reductions can be achieved through decreasing demand for steel and Scenario B shows that energy efficiency improvements also contribute to emission reductions. Increases in material efficiency can further reduce demand for steel. Measures to achieve material efficiency include: lightweight product design, increasing product lifespans, using products more intensively, better manufacturing processes and the re-use of steel without melting it (Allwood et al. 2011). The substitution of steel with lower emissions-intensive materials, such as aluminium in vehicles, can also lower steel demand. The relatively small difference between the out-comes of Scenarios B and C shows that one of the largest constraints to rapid decarbonisation using technology available today is the availability of scrap metal for EAF production.

To rapidly decarbonise the steel sector, investments must be made to optimise the energy and emissions performance of existing production routes (IEA 2015), such as increasing process integration, using process gas streams or capturing the emitted carbon. Such optimisations are assumed in Scenarios B and C.

CEMENT SECTOR: TRENDS

Cement demand can generally be said to reflect a country's demand for housing, infrastructure, and level of urbanisation (Davidson 2014). In Figure 3, we show the total (historical and projected) cement production for the world and three regions: the EU, China and Nigeria, Sub-Saharan Africa's largest cement producer (see page 5 of this briefing).

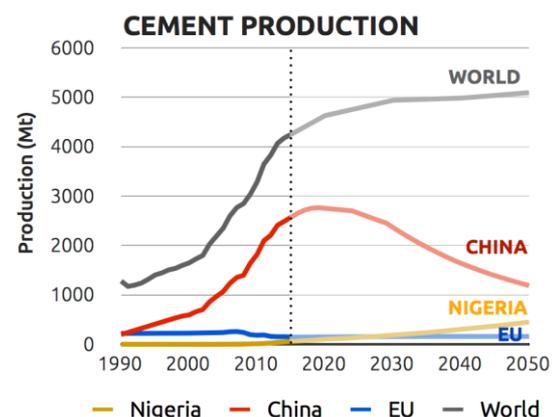


Figure 3: Cement production worldwide and in three countries in different stages of development. Historical data 1990–2015 and projections up to 2050. Data sources are listed in Annex B.

European cement production has been mostly stable, decreasing recently in the wake of the 2008 financial crisis. China's production has been rising continuously since the turn of the millennium, but is projected to peak within the next decade. Nigeria's took about a decade

longer to reach comparable growth rates, which have since exceeded China's. Worldwide, cement production is projected to keep rising, mainly driven by growth rates in the developing world—chiefly South Asia and Sub-Saharan Africa (van Ruijven et al. 2016), where Nigeria's cement industry has boomed in recent years.

Cement making consists of two distinct steps: clinker production, followed by blending of clinker into cement in a cement mill. Emissions from the cement industry can be grouped into three categories: process emissions, direct energy-related emissions and electricity-related emissions.

The clinker production process includes the conversion of limestone into clinker, during which CO₂ is released as a by-product. These emissions are termed "process emissions." Typically, these cover about 50% of cement-related emissions. The clinker production is also the most energy-intensive stage of cement making, and largely determines direct energy-related emissions (Blok 2007). In clinker production, one can distinguish the so-called "wet" and "dry" kiln types. In the wet kiln, the minerals fed into the kiln are combined with water to create a slurry that substantially increases energy intensity because of the additional heat needed to evaporate the water. For this reason, clinker production with the dry method is much more common nowadays (European Commission 2010; Xu et al. 2012; WBCSD 2016).

Global cement-related emissions rose from nearly 1.0 Gt in 1990 to above 2.6 GtCO_{2e} in 2010, corresponding to a near-doubling of the share of cement in global GHG emissions from 2.8% to 5.5% in the period 1990–2010 (Fischedick et al. 2014).

CEMENT SECTOR: SCENARIOS

There are several options to reduce emissions in the cement sector, which can be broadly grouped into four categories: clinker substitution, efficiency improvements, use of alternative fuels (both in direct energy and in the power sector), and demand reduction (IEA 2009).

Clinker substitution allows reaching low clinker/cement ratios and thereby limits process emissions. It is possible using materials such as natural pozzolans, coal fly ash and blast furnace slag (Cembureau 2012). As a result clinker/cement ratios of 50% or less can be reached, c.f. ~73% average today in the EU (WBCSD Cement Sustainability Initiative 2014). However, it must be noted that the availability of fly ash and slag would be restricted if the steel sector and power sector were to decarbonise (through phase-out of blast

furnaces and coal-fired power plants, although coal with CCS would remain an option to produce fly ash). This implies that the options for decarbonising the cement sector by reducing clinker demand are limited in a decarbonisation scenario. For this reason, they are not analysed in detail here. RD&D on clinkerless cement, however, is ongoing, and may present opportunities for emission reductions in the future (Cemnet 2011).

In the scenarios constructed for the cement sector, the key elements are:

- **Scenario A** is a **current trends** scenario that illustrates the effect of demand changes in cement based on literature (see Annex B), with shallow efficiency improvements and shallow fuel mix decarbonisation.
- **Scenario B** is a **decarbonisation** scenario that follows the same demand development as Scenario A, with decarbonisation of electricity production, strong improvements in efficiency, electrification measures, and a reduction of the clinker/cement ratio to, at most, 70%.
- **Scenario C** is a scenario with **steps towards circularity** that illustrates the effect of material substitution leading to an avoidance of cement demand of 20% as compared to A and B in 2050, along with a fully decarbonised power sector and 100% zero-carbon fuels by 2050.

Options for increasing energy efficiency include operating installations at full capacity and improving the thermal efficiency of clinker kilns by using best available technologies. Fuel switching in direct energy supply could include replacing fossil fuels with biomass or waste (Neuhoff et al. 2014).

The demand reduction in Scenario C implies product substitution. This could be a partial substitution of the cement needed for concrete production by using aggregates of cement with e.g. crushed concrete (Fischedick et al. 2014), wood waste ash from biomass combustion (Ban & Ramli 2011; Turgut 2007), cotton waste from the spinning industry, and limestone powder waste from limestone processing factories (Algin & Turgut 2008).

Alternatively, it could be a full replacement of concrete with other materials, such as steel or aluminium (which, however, should have their own decarbonisation pathways that may require reductions in production), Cross-Laminated Timber (Circle Economy & Ecofys 2016), or cement-free concrete, such as alkali-activated concrete (Neuhoff et al. 2014; Bilek et al. 2016). We choose a value of 20% demand avoidance to get an idea of the emission reduction potential;

however, this number is meant solely for demonstration, and not based on literature.

We have analysed the historical and future pathways of emissions from the cement sector under the above scenarios for the EU, China and Nigeria to highlight three very different developments in cement sectors worldwide.

Cement production in the EU decreased in the wake of the financial crisis in 2008 and has not recovered since—standing at 67% of 1990 production in 2014.

In contrast, cement production in China has been consistently increasing and is now at levels about 15 times higher than in 1990 (USGS 2014; Ke et al. 2013).

Even more extreme has been the case of Nigeria, where cement production has seen a massive increase in recent years—by an estimated rate of close to 40% a year from 2008–2015 (The Business Year 2016; Ohimain 2014). For comparison, Chinese cement production increased by an average rate of “only” 11% per year from 1990–2014. As construction booms in Sub-Saharan Africa, driving cement demand

(Bloomberg 2016), Nigeria has emerged as the largest cement producer in Sub-Saharan Africa, overtaking South Africa around 2010 (USGS 2016).

The scenario outcomes for the EU, China and Nigeria are given in Figure 4. The different development implied for these countries is clear: continued plateauing or decrease for the EU, peaking around 2020 for China and a continued strong increase for Nigeria.

Across these countries, Scenario B would result roughly in a 20% emission reduction in 2050 compared to Scenario A. Scenario C would lead to a roughly 50% reduction. **Cumulative** emissions until 2050 would, however, decrease by only about 10–15% under Scenario B (compared to A), and by 20–40% under Scenario C.

The presence of process emissions means that even under decarbonisation and steps towards circularity, substantial emissions will remain. To help mitigate these emissions, innovative options for low-carbon products and possibly the use of CCS on industrial scales will be necessary.

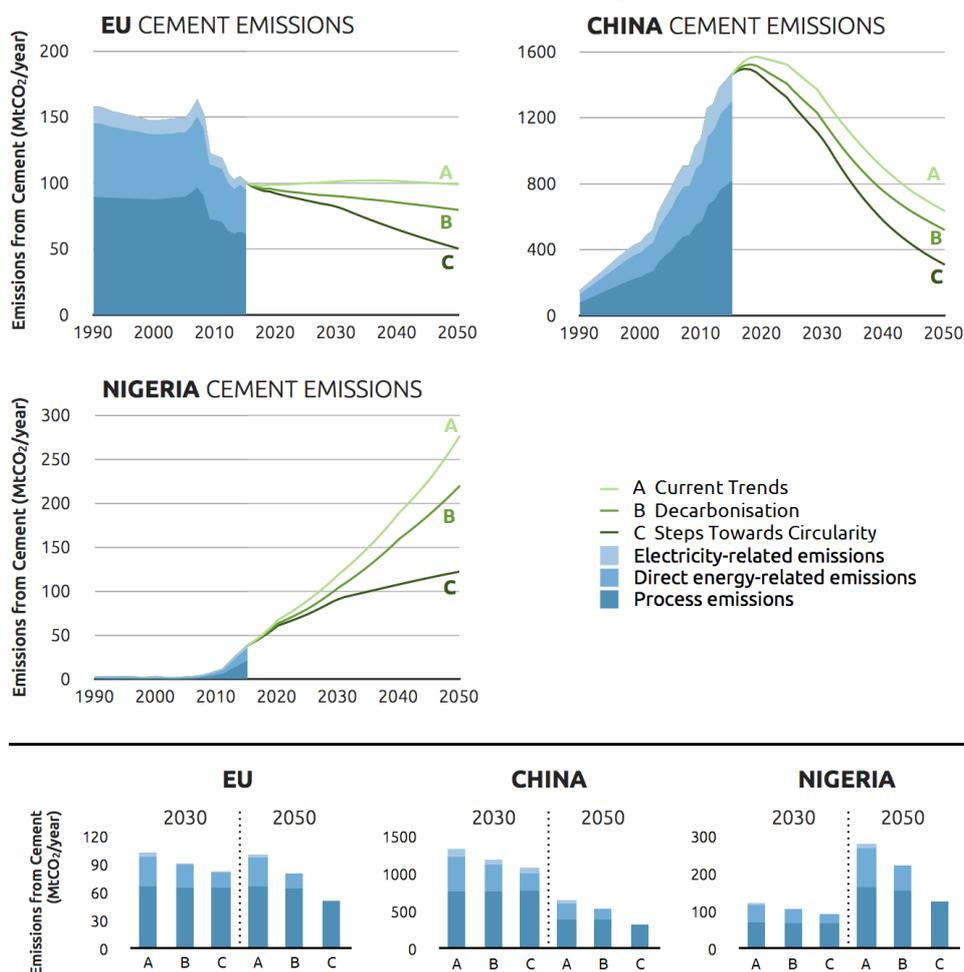


Figure 4: (Top) Emissions from cement making in the EU, China and Nigeria, historically (1990–2015) and in the future (2016–2050) under the scenarios as detailed above. Data sources and assumptions used to construct the scenarios are given in Annex B. (Bottom) The split between process-related, direct energy-related and electricity-related emissions in 2030 and 2050 under the three scenarios.

CONCLUSION

As the presented scenarios show, the extent to which emissions from steel and cement can get close to zero in this century depends on future changes in efficiency, energy supply and production routes.

Why is it so difficult to get emissions to near-zero levels? In **steelmaking**, the most common method—the BF/BOF route—requires high-carbon coke as fuel. Recycling of scrap steel through the EAF route avoids large amounts of emissions associated with fossil fuel combustion, but scrap availability is limited, which will constrain the shift towards a circular steel sector.

In **cement making**, the bottleneck lies in process emissions. Even a fully decarbonised

energy supply would not affect the ~50% of emissions from cement that are process-related. One way to reduce these is clinker replacement, or substituting cement altogether.

There are other viable decarbonisation options through innovative production routes and product substitutions that need to be explored with targeted RD&D efforts, so that these alternatives can develop and eventually mainstream in the steel and cement industry, in order to achieve reductions beyond the scenarios outlined in this briefing. This can include the need for CCS technologies if it turns out full decarbonisation is not possible.

ANNEX A: METHODOLOGY

The calculations in this analysis were performed using a prototype of the PROSPECTS model, under development by the Climate Action Tracker team¹. The prototype used for this study contained simplified modules for the power, cement and steel sectors, interlinked such that electricity-related emissions could be allocated to the end-use sectors in industry. Logic charts for the calculations in these sectoral modules are shown in Figure 5, Figure 6 and Figure 7. As indicated in the legend, some of these metrics are necessary as input data to run the calculations; the data sources used are given in Annex B.

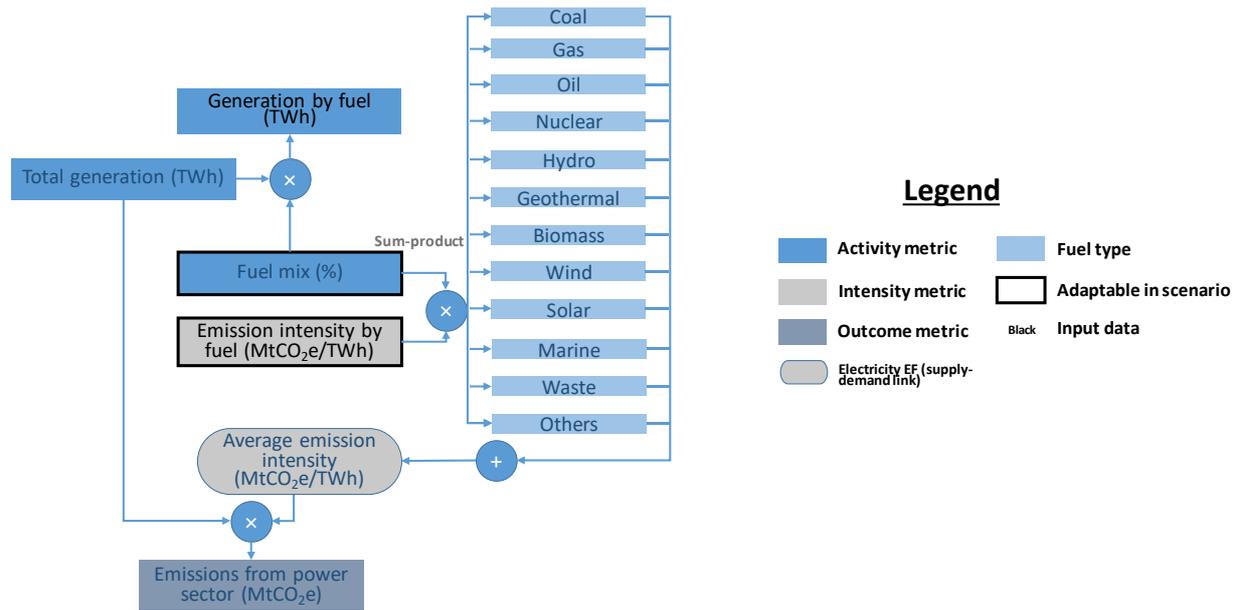


Figure 5: Flowchart showing the logic of the power sector in the present analysis. EF = Emission factor.

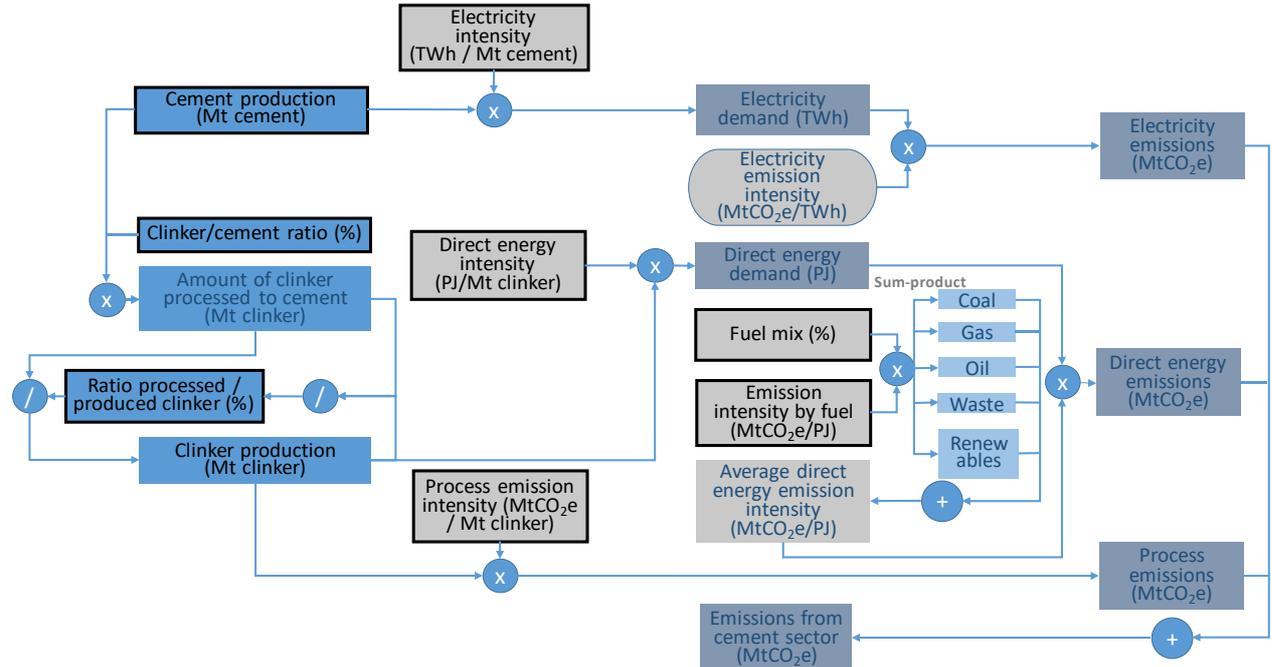


Figure 6: Flowchart showing the logic of the cement sector in the present analysis.

¹ PROSPECTS stands for **Policy-Related Overall and Sectoral Projections of Emission Curves and Time Series**. The aim of the model is to estimate historical emissions time series across all economic sectors, coupling energy supply and demand, and allow for user-defined scenarios of activity/intensity indicators for emissions projections. A full documentation of the PROSPECTS approach is expected to be published in 2018.

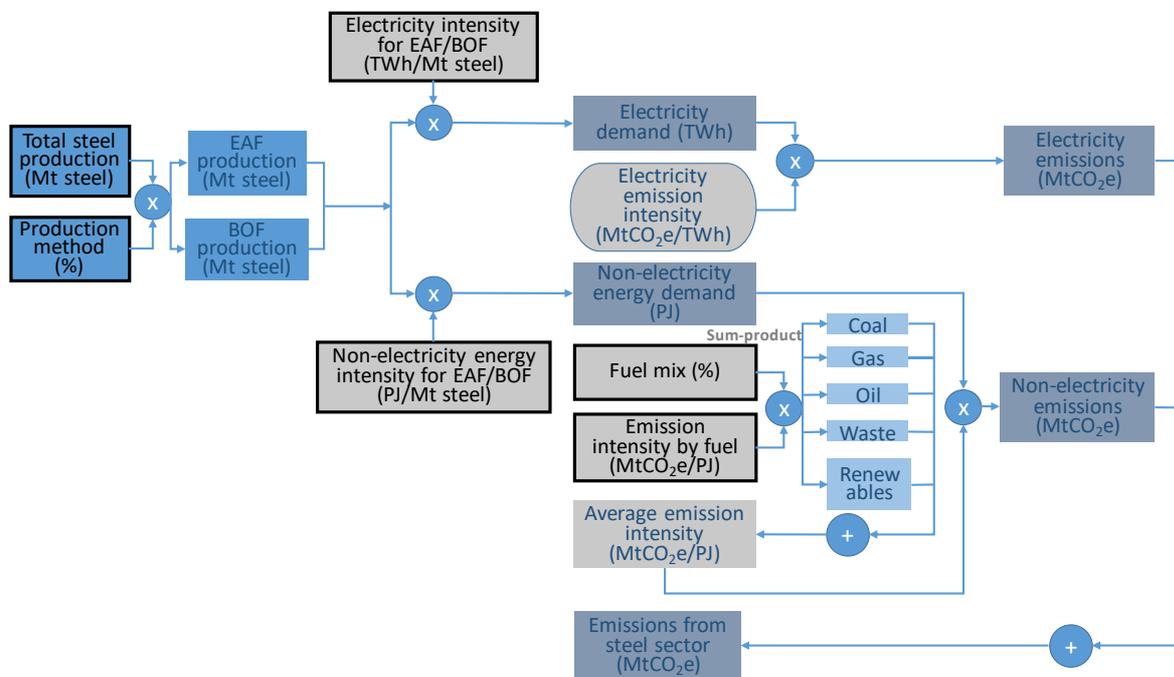


Figure 7: Flowchart showing the logic of the steel sector in the present analysis.

ANNEX B: DATA

The precise definitions of the scenarios for the cement sector are presented in Table 1. All other indicators that influence the future pathway were kept constant throughout, if not mentioned in the table. The definitions for the steel sector, similarly, are given in Table 2. All sources used for historical data collection, as necessary for the calculations shown in Annex A, are listed in Table 3. We furthermore provide a short comparison of results from our approach to literature values of emission estimations from cement and steel in the relevant regions in Table 4 to validate the outcome of our simplified model.

Table 1: Breakdown of the pathways of key indicators used in the definition of the cement sector scenarios. ETP refers to (IEA 2016d).

| Lever | Metric | Scenario A (current trends) | Scenario B (decarbonisation) | Scenario C (steps towards circularity) | Affects which emissions? |
|--------------------------|--|---|--|---|------------------------------|
| Demand | Cement activity (t cement / year) | EU: Following trends in CTI until 2030 (ClimateWorks Foundation 2016); growth rate of cement production for OECD economies in ETP for 2030-2050. China and Nigeria: Following projections of cement production growth rate in (van Ruijven et al. 2016) (West Africa growth rate used as proxy for Nigeria). | | Follow current trends until 2030, then follow growth rates that correspond to avoiding 20% of the 2050 cement production in scenario A/B. | All |
| Efficiency | Energy efficiency (PJ / t clinker) | Follow trend in ETP 6DS (By OECD / non-OECD) | Follow trend in ETP 2DS (By OECD / non-OECD) | | Direct energy-related |
| | Electricity intensity (kWh / t cement) | Follow trend in ETP 6DS (By OECD / non-OECD) | Follow trend in ETP 2DS ² (By OECD / non-OECD) | | Electricity-related |
| Direct energy mix | Thermal energy fuel mix (%) | Remains as is (inspired by ETP 6DS) | 40% RE for OECD; 30% RE for non-OECD (inspired by ETP 2DS) | 100% RE by 2050 | Direct energy-related |

² This includes not only improved efficiency (reducing the intensity indicator), but also electrification, which may drive the electricity intensity up instead of down while reducing the direct energy intensity.

| | | | | | |
|----------------------------------|---|---|--|--|--|
| Power mix | Power sector fuel mix (%) | Follow trend in ETP 6DS (For EU, China) Remain at current levels (Nigeria) | EU, China: Follow trend in ETP 2DS Nigeria: Linear transformation towards ETP 2DS 2050 values for India used as proxy | Follow 2DS until 2030, then linear trend to 100% zero-emission in 2050 | Electricity-related |
| Power emissions intensity | Electricity generation intensity (gCO ₂ / kWh) | Following Current Policies Scenario in IEA World Energy Outlook 2016 (IEA 2016e). | Following 450 scenario in IEA World Energy Outlook 2016 (IEA 2016e). | | Electricity-related³ |
| Clinker substitution | Clinker/cement ratio (%) | Remains as is | Linear decrease towards 70% clinker/cement ratio (if applicable, otherwise remains as is), based on (CSI 2009). | | Process-related Direct energy-related |

Table 2: Breakdown of the pathways of key indicators used in the definition of the steel sector scenarios.

| Lever | Metric | Scenario A (current trends) | Scenario B (deep decarbonisation) | Scenario C (steps towards circularity) | Affects which emissions? |
|----------------------------------|---|--|---|---|------------------------------|
| Demand | Steel activity (t steel per year) | The steel demand trajectories of all scenarios are identical, which is similar to the approach taken by the IEA Energy Technology Perspectives modelling of the steel sector (IEA 2016d). Steel demand in China follows the BAU trajectory of (Zhang et al. 2016a), while demand in the EU follows the growth rates projected in (Boston Consulting Group & Steel Institute VDEh 2013a). World demand projections displayed in Figure 1 are from (van Ruijven et al. 2016). | | | All |
| Production method | % share of production from BF-BOF route vs EAF route | China: Follows base case of (Zhang et al. 2016a) EU: Follows assumptions of (Ecofys 2015) | | China: Follows structural adjustment case of (Zhang et al. 2016a) EU: Follows assumptions of (Allwood & Cullen 2012) | All |
| Efficiency | Electricity intensity (TWh/Mt steel) | China and EU: Incremental energy efficiency improvement rate from (van Ruijven et al. 2016) | Convergence in 2050 at electricity intensities from (WWF & Ecofys 2011). | | Electricity-related |
| | Direct energy intensity (PJ/Mt steel) | China and EU: Incremental energy efficiency improvement rate from (van Ruijven et al. 2016) | Convergence in 2050 at direct energy intensities from (WWF & Ecofys 2011). | | Direct energy-related |
| Direct energy fuel mix | Direct energy fuel mix (%) | China: follows non-OECD 6DS trend from IEA ETP 2016. EU: As the historical direct energy fuel mix from the OECD 6DS scenario from IEA ETP 2016 is substantially different to the EU historical values from the IEA energy balances (with a significantly higher coal share), the EU direct energy fuel mix remains fixed at the latest historical value (2014) (IEA 2016d; IEA 2016b). | China: follows non-OECD 2DS trend from IEA ETP 2016. EU: As the historical direct energy fuel mix from the OECD 2DS scenario from IEA ETP 2016 is substantially different to the EU historical values from the IEA energy balances (with a significantly higher coal share), the EU direct energy fuel mix remains fixed at the latest historical value (2014) (IEA 2016d; IEA 2016b). | | Direct energy-related |
| Power mix | Power sector fuel mix (%) | Follow trend in ETP 6DS (For EU, China) | EU, China: Follow trend in ETP 2DS | Follow 2DS till 2030, then linear trend to 100% zero-emission in 2050 | Electricity-related |
| Power emissions intensity | Electricity generation intensity (gCO ₂ / kWh) | Following Current Policies Scenario in IEA World Energy Outlook 2016 (IEA 2016e). | Following 450 scenario in IEA World Energy Outlook 2016 (IEA 2016e). | | Electricity-related |

³ The effect of this indicator on overall cement-related emissions is extremely small, of the order of 1%, as compared to keeping all values constant across the three scenarios.

Table 3: Data sources used for historical data collected for the analysis. Wherever data gaps would exist, linear interpolation between available data points is used unless mentioned otherwise. Wherever data was only available until 2014, an extrapolation of the 2010-14 trend was used to estimate values for 2015.

| Sector | Quantity | Unit | EU | China | Nigeria |
|---|--|--|--|---|---|
| Electricity | Electricity generation by source | TWh | From (IEA 2016f) for all countries | | |
| | Emissions intensity by source | gCO ₂ / kWh | Calculated from (IEA 2016a; IEA 2016f) for all countries | | |
| Cement | Cement production ⁴ | Mt / year | All data from (WBCSD 2016) ⁵ | 1990 value from (Ke et al. 2013); 1998-2014 series from (USGS 2014); extrapolation of trend 2010-14 for 2015 | 1990-2008 time series from (Ohimain 2014); 2011 value from (Ohunakin et al. 2013), 2015 value from (The Business Year 2016); interpolation for missing years. |
| | Clinker production | Mt / year | | Assumed to be equal to cement production multiplied by clinker/cement ratio (Ke et al. 2013); this is equivalent to assuming that cement production relies on 100% local clinker. | Calculated from cement production and clinker/cement ratio, assuming that clinker used for cement production is 95% local material (PanAfrican Capital 2011). |
| | Clinker / cement ratio | % | | 2005-2011 data from (Ke et al. 2013); extrapolation until 1990 and 2015 done using growth rate in clinker/cement ratio for "China, Korea and Japan" from (WBCSD 2016). | Values for "Africa" from (WBCSD 2016) |
| | Electricity intensity of cement production | kWh / t cement | | Values for "China, Korea and Japan" from (WBCSD 2016) | |
| | Direct energy intensity of cement production | MJ / t clinker | | | |
| | Fuel mix of direct energy | % | From (IEA 2016f) for all countries | | |
| | Emissions intensity of direct energy | gCO ₂ / MJ | Calculated from (IEA 2016a; IEA 2016f) for all countries | | |
| | Process emissions intensity | tCO ₂ / t clinker | Constant; from (Gibbs et al. 2000) | | |
| | Steel | Steel production | Mt / year | All data from (World Steel Association 2016a; World Steel Association 2013a) | |
| Production method | | %production from EAF route vs BF-BOF route | All data from (World Steel Association 2016a; World Steel Association 2013a). We assume that the statistics in these sources for the "production of steel in electric furnaces" is production of steel through 100% scrap-based EAF. | | |
| Electricity intensity of steel production EAF route | | TWh/Mt steel | EAF route: due to limited data availability of country-specific final energy intensity of EAF steelmaking, a global average value is used from (World Steel Association 2013b). The split of final energy | | |

⁴ Data on cement production worldwide (used only in Figure 3) are from (van Ruijven et al. 2016) for 1990-1997 and from (USGS 2014) for 1998-2014; the projection in the figure is based on the growth rates implied in (van Ruijven et al. 2016).

⁵ Note that coverage of cement production is not comprehensive for many regions/countries in this database, but close to 100% for the EU.

| | | | | |
|--|--|------------------------|--|--|
| | Direct energy intensity of steel production EAF route | PJ/Mt steel | between electricity and direct energy was obtained from (Worrell et al. 2010). | |
| | Electricity intensity of steel production BF-BOF route | TWh/Mt steel | Final energy intensity was obtained from (Zhang et al. 2016a) | Final energy intensity was obtained from (ESTEP & EUROFER 2014) |
| | Direct energy intensity of production BF-BOF route | PJ/Mt steel | The split of final energy between electricity and direct energy was obtained from (Worrell et al. 2010). | The split of final energy between electricity and direct energy was obtained from (Worrell et al. 2010). |
| | Fuel mix of direct energy | % | From (IEA 2016f) for all countries | |
| | Direct energy emission intensity | MtCO ₂ e/PJ | Calculated from (IEA 2016a; IEA 2016f) for all countries | |

Table 4: Comparison of outcomes from this study for historical emissions time series to emission estimates found in literature.

| Country/region | Quantity | Literature value | Estimation in this study |
|----------------|--|---|---|
| China | Emissions from cement | 1.1 – 1.4 GtCO ₂ (2010) (Ke et al. 2013) 1.4 GtCO ₂ (2010) (van Ruijven et al. 2016) Time series from 0.10 GtCO ₂ in 1990 to 1.42 GtCO ₂ in 2014 (Boden & Andres 2016). | 1.1 GtCO ₂ (2010) From 0.13 GtCO ₂ in 1990 to 1.62 GtCO ₂ in 2014. Yearly difference to (Boden & Andres 2016) series ranging from 1% to 22%, average 14%. |
| | Emissions from cement, excl. electricity-related | 0.6 – 1.1 GtCO ₂ (2010) from different studies compiled in (Liu et al. 2015). | 0.9 GtCO ₂ in 2010 |
| | Direct energy related emissions from steelmaking | Over 2001 – 2010, an increase from 400 MtCO ₂ to 1,800 MtCO ₂ (Tian et al. 2013) 2010: 1,450 MtCO ₂ (Wen et al. 2014) 2010: 1,400 MtCO ₂ (Chen et al. 2014) | Over 2001 – 2010, an increase from 330 MtCO ₂ to 1,600 MtCO ₂ |
| EU | Emissions from cement | 174 MtCO ₂ (2007) 158 MtCO ₂ (2008) 122 MtCO ₂ (2011) (European Commission n.d.) | 161 MtCO ₂ (2007) 151 MtCO ₂ (2008) 118 MtCO ₂ (2011) |
| | Emissions from steelmaking | Average direct energy related emissions of 250 MtCO ₂ over 2005 – 2008 (Ecofys et al. 2009) Over 1990 – 2010, direct energy and electricity related emissions fell from 298 MtCO ₂ to 223 MtCO ₂ (EUROFER 2013) | Average of 270 MtCO ₂ over 2005 – 2008 Over 1990 – 2010, direct energy and electricity related emissions fell from 360 MtCO ₂ to 260 MtCO ₂ |
| Nigeria | Emissions from cement | Time series from 1.7 MtCO ₂ in 1990 to 5.0 MtCO ₂ in 2008 (Boden & Andres 2016). | From 2.4 MtCO ₂ in 1990 to 4.3 MtCO ₂ in 2008. Yearly difference to (Boden & Andres 2016) series ranging from 17% to 35%, average 25%. ⁶ |

⁶ While the CDIAC (Boden & Andres 2016) time series runs until 2014, our own emissions estimates are based on an interpolation of cement production between 2008 and 2015 (see Table 3), recent data which most likely was not used for the time series of CDIAC running until 2014. As the 2015 value of cement production is substantially higher than that of 2011 and 2008, implying a very recent strong increase in cement production, we do not compare these time series after 2008.

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