The impact of future power generation on cement demand: an international and regional assessment based on climate scenarios

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The impact of future power generation on cement demand: an international and regional assessment based on climate scenarios[☆]

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Abstract

Concrete is the most widely used manmade material in the world with an annual production of about 10 billion tons globally. Its use outpaces that of historically important materials such as wood or stone in modern urbanism. Concrete is closely tied to the energy transition. As a structural material, concrete is used in multiple sectors, including energy. Because the concrete content of a power plant varies depending on the technology, the energy transition is expected to impact future demand for concrete. At the same time, concrete production is known to be highly polluting as one of its major components is cement, produced by an industry that is one of the main emitters of carbon dioxide worldwide. This dual aspect explains the aim of this study: understanding concrete (and therefore cement) demand under the energy transition policies described in the IEA's 2017 Energy Transition Policy (ETP) report and quantifying CO_2 emissions from cement production for the energy sector. Based on a simple model, the study is looks at global and regional levels to take into account potential local disparities. The results demonstrate that the decarbonisation of the power sector will have a limited impact on global cement demand, but that it could be more challenging for some regions where the new power production mix would require large concrete structures.
This model could be a useful decision-making tool in assessing the relative impact of any public energy transition scenarios on raw materials such as cement at the highest level of disaggregation, as well as enabling better sub-sectorial screening.

Keywords: Energy transition, concrete, cement, power sector, construction materials

JEL Classification: Q42, Q51, Q53

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1. Introduction

1.1 Concrete requirements for power generation technologies

As a consequence of climate change mitigation, we are seeing new energy transition policies aimed at reducing greenhouse gas (GHG) emissions and containing global warming in the wake of the Paris Agreement (COP21). Decision-making takes place in a complex and increasingly global context. In the context of technological, social and environmental challenges, climate scenarios are being developed by major international organisations such as the International Energy Agency (IEA) and the World Energy Council (WEC), and are important benchmarks both for policies and for industry. Climate scenarios are also being developed by non-governmental organisations (NGOs) such as the World Wide Fund for Nature (WWF) and Greenpeace, and by private energy companies like BP and Shell. These scenarios all agree on the need for more power plants based on variable renewable energy.

From 2008 to 2017, world renewable energy[1] capacity increased from 1,057 GW to 2,179 GW [1]. In 2017, renewable energy capacity continued to grow at record levels. Offshore wind investment, for example, increased nearly four-fold from 2013 to 2016 and is expected to grow further [2]. Nevertheless, total investment value in renewables fell in 2016 (in US dollar terms) due to the large drop in technology costs. Most renewable energy technologies, and other low-carbon technologies such as electric vehicles, require considerable mineral resources. Many studies have focused on these new material demands, especially for rare earth elements [3,4] and minor metals such as cadmium, chromium, cobalt and lithium, to identify material bottlenecks and analyse potential critical materials that could limit large-scale diffusion of low-carbon technologies [5,6,7,8]. The energy required to extract and then refine such resources is often pinpointed. Hodgkinson and Smith [9] presented the link between the aim of sustainable development and the need to carefully plan our resource extractions through a detailed policy framework. They encouraged and supported the widespread adoption of mitigation strategies in mining and mineral processing, recycling and closed-loop resource usage. They provided a synthetic roadmap of adaptation and mitigation strategies at the global scale for a climate-smart mining and recycling strategy to comply with the Paris Agreement and UN 2030 Agenda for Sustainable Development. Without any doubt, the energy transition to a low-carbon economy will involve substantial amounts of minor metals. It will also require an increased use of structural (or bulk) materials, such as aluminium, copper, nickel or cement [10]. Such materials may be less constrained by available reserves than by their production processes. Indeed, aluminium, iron and steel, like cement, are known to be very energy-intensive. Although future aluminium, iron and steel demand for power generation have been examined in the literature [11,12,13,14], relatively few studies have tackled the interaction between the power sector transition and subsequent cement demand. This is nonetheless an important issue as cement is often mentioned as a crucial material due to the large volume required in building energy technologies and its high environmental impact. In

[1] IRENA considers the following energy sources renewable: hydropower, marine energy, wind energy, solar energy, bioenergy (solid biofuels and renewable waste, liquid biofuels, biogas) and geothermal energy.

addition, cement is one of the major components of concrete, which is widely used in buildings and infrastructure. With a total production volume of about 6 billion m^3 in 2017, concrete is the most commonly used building material [15]. Heavier, more elastic and more resistant than wood, stone and most construction materials, its use has outpaced that of these important traditional materials in modern urbanism. Nowadays, 80% of individual housing and 90% of collective housing is built using concrete [15]. It is also crucial for building larger structures such as hospitals and factories, and in the construction of new transport infrastructures (roads, bridges, etc.). But concrete is also a key material in the energy sector, which relies on the building of power plants and electrical connections. In the power sector, it is used in the foundations of nuclear power plants for example, and in the pedestals and towers of wind turbines [16,17,18]. For example, the European Pressurised Reactor (EPR)[2] at Flammanville (France) has required 400,000 m^3 of concrete. Dams are also large concrete consumers [19]. The world's largest concrete structure is the Three Gorges Dam in China, which used about 26 million m^3 of concrete.[3] In the energy sector, concrete is a key material for the building of power plants and can be also used for thermal energy storage [20].

In this article, we consider several energy transition scenarios and compare their impact on demand for concrete and cement in the power sector. To quantify these demands, the concrete content of each technology used has to be known. Data has been pooled from different sources [10,21,22, 23] in order to assess concrete needs in the power sector (Table 1). However, due to lack of data on the future intra-technology systems disaggregation in these prospective energy scenarios, average figures of material content per family of technology type have been considered. Given the diversity of technical solutions and the variety of site-specific characteristics, these concrete content may slightly differ according to the regions. However, this paper will intend to stay in line with scientific literature by using average life cycle inventories which will differ inevitably from the real material inventory at a micro-level. Indeed, according to literature the differences in material intensities are sometime more important within an energy technology system along with the size (e.g. onshore wind system where the concrete content could vary between 72 and 558 t/MW only in France [24], or in a lesser extent in geothermal between 80 and 132 t/MW within two kinds of systems in Indonesia and Netherlands [23]). For example, Zimmermann et al. [25] studied the concrete demand from a large-scale deployment of wind energy in Germany and made the assumption that onshore wind turbines required more concrete per installed MW than offshore wind turbines, while offshore wind turbines require a higher percentage of steel for the construction. This regional assumption differs from our global assumptions on concrete demand for wind technologies.

Please insert Table 1 here

[2] A third generation Pressurised Water Reactor (PWR) design.

[3] http://www.china-embassy.org/eng/zt/sxgc/t36512.htm

In addition to power generation technologies, the transmission and distribution of electricity from production sites to individual consumers should be taken into account. Vidal [10] tried to quantify the concrete demand required for interconnection, although with a large range of uncertainties. The estimated overall concrete content of connectivity could vary between 100 and 500 Mt/yr based on extrapolating the material intensities in Harrison et al. [26],[4] which is more than ten times the concrete volume required for the power generation according to Vidal's estimations[5] [10]. Harrison et al. [26] estimated that concrete represented 53% of the raw materials used to build the whole UK electricity transmission system.[6] However, their results are inferred from specific indicators related to technology activities and not from installed technology capacities.[7] Due to a lack of accurate data at the world scale, the electrical transmission system and potential carbon capture units have therefore not been taken into account in this paper. Consequently, in the remainder of this paper, technologies with and without carbon capture will be aggregated. For example, coal and coal with CCS (carbon capture and storage) will both be referred to simply as coal.

1.2 The use of scenarios to anticipate future concrete demand

The issue of future concrete demand from the power sector can be tackled at the global or regional levels, based on existing scenarios (from the IEA for example) or supposed electrical mixes (Table 2). Future concrete demand will vary widely according to the assumptions made on technology concrete content and the scenario considered. This was particularly emphasised by the French National Energy Research Coordination Alliance (ANCRE) [27], which considered future annual concrete demand would fluctuate from 30 Mt/y to more than 100 Mt/y under the French energy transition scenarios for 2050. Taking into account the diversity of future electricity mixes worldwide, it is not reasonably possible to extrapolate these results from France at the global scale. One of the most consistent studies in the literature was conducted by Hertwich et al. [28] using IEA scenarios (BLUE Map scenarios, 2010) [29]. By conducting an integrated life-cycle assessment of electricity supply scenarios, the authors estimated future aluminium, copper, cement and iron requirements and underlined potential concerns about copper supply by 2050. However, a limit of their study is that some technologies, such as combined heat and power plants, bioenergy and nuclear sources, which have a significant impact in the future power sector mix, were excluded due to more complicated life-cycle inventories (comprehensive assessment of the food system for bioenergy or conflicting results of competing assessment approaches in the case of nuclear). In addition, material requirements were based on activity and not directly on new installed capacity and could therefore lead to rough estimations.[8]

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[4] Harrison et al. largely took their data for embodied energy and carbon in materials from the Inventory of Carbon and Energy, a database of construction materials compiled by the University of Bath [55].

[5] Between 7 Mt/yr (Blue Map, IEA ETP 2010) and 10 Mt/yr of concrete would be required globally for power generation by 2050 [56].

[6] The transmission system includes overhead lines, underground cable, substations and transformers.

[7] Demand for materials is better assessed in terms of capacity than activity, since capacities built but not used have still consumed materials.

[8] In the supporting information, authors described the matrix product used to calculate absolute emissions and resource, one of the terms of which was a "matrix of emission or resource load intensities by activity".

Please insert Table 2 here

Given its importance for power plant construction and its significant carbon footprint, concrete is an important and challenging material for the energy transition. The aim of this article is therefore to quantify the future concrete needs of the power sector under several climate scenarios and gain better insight into the electricity mix evolution in the light of future low-carbon technology implementation. Our contribution to the literature is three-fold. Firstly, the dataset used in this paper is the latest available (IEA ETP 2017) [30]. Secondly, we take into account the decommissioning process of existing power plants. And thirdly, we conduct both a global and a regionalised approach regarding cement demand while taking into consideration all power sector technologies. This is due to the fact that both electricity mixes and climate policies differ significantly from one region to another.

As the main environmental challenge related to the use of concrete concerns cement production, the cement manufacturing processes and market are discussed in Section 2. Section 3 describes the model developed to determine the evolution of demand for concrete and cement in the power sector. Section 4 presents our main global- and regional-scale results and related comments, while Section 5 summarises our findings and provides policy recommendations and research perspectives.

2. The cement sector

Cement is an essential component of concrete. Chemically, concrete is a composite material containing several mineral materials. It is made up of inert materials called aggregates (sand, gravel, etc., 60 to 75% of composition in volume), a binder (i.e. a material able to agglomerate, generally cement, but sometimes clay or bitumen, 10 to 20%); and water and other admixtures used to modify the physical and chemical properties of the mixture (Figure 1). In current usage, and in this study, the term concrete designates “cement concrete”.[9] Cement is a manufactured compound that is classically composed of clinker,[10] gypsum and other admixtures (such as limestone, blast furnace slag, coal fly ash,[11] and natural pozzolanic materials).

Please insert Figure 1 here

2.1 Overview of the cement market

The cement industry has grown relatively fast, along with concrete demand, largely due to Chinese demand growth (Figure 2). Its production increased by around 86% during the 2006-2013 period, mainly explained by growing Chinese urbanisation. However, Chinese cement production has

[9] The terms “clay concrete”, if the binder used is clay, and “asphaltic concrete”, if the binder is bitumen, are also used.

[10] Clinker is produced by sintering limestone and aluminosilicate materials.

[11] Generated by the burning of coal and waste materials for calcination.

stagnated since 2013 due to a slowdown in the real estate market since 2014. Total cement production worldwide therefore peaked in 2014 with annual production of about 4.1 billion tons (Gt), and has since stagnated [31]. This volume represents an annual increase of 23% compared to 2010, and 155% compared to 2000. As seen in Figure 2, the 13 largest producing countries in 2017 (China, India, USA,[12] Turkey, Brazil, Russia, Iran, Indonesia, South Korea, Vietnam, Saudi Arabia, Japan and Egypt) together account for 70% of world production, while China alone represents almost 60% of global production, with 2.4 Gt in 2017.

Please insert Figure 2 here

Cement is a very local market. It involves only a small volume of international trade. According to [32], only 179 million tons of cement was traded globally in 2016 (3.6% of production).[13] This is easily explained by the fact that cement is a commodity that involves very high transport costs due to its weight, relative to its market value. It is usually said that cement could not economically be hauled beyond 200 or at most 300 km.[14] Production is therefore generally located at a reasonable distance from operating activities in order to minimise transport costs. The largest cement exporters are currently China, Turkey, Japan and Thailand, while the largest importers are the United States of America, Bangladesh, Sri Lanka and Singapore. In 2016, the largest trade flows were from Canada to the USA (4.5 Mt), from India to Sri Lanka (4.3 Mt), from China and Thailand to Bangladesh (respectively 4.1 Mt and 3.8 Mt), and finally Japan to Singapore (3.5 Mt), illustrating the predominance of border trade.

2.2 Cement manufacturing and environmental impact

The cement sector is currently the third-largest industrial energy consumer and the second-largest industrial CO_2 emitter globally [33]. That makes it one of the most emitting industries worldwide with approximately 25 to 27% of total industrial emissions (i.e. 5 to 7% of global CO_2 emissions) [34], and it is responsible for 12 to 15% of industrial energy use worldwide [35].

High GHG emissions are partly due to the high energy needs for the process but also, intrinsically, to chemical reactions in cement clinker production. Depending on the different production processes, the average energy intensity for cement production ranges from 4 to 6 GJ per ton[15] of cement [36]. Figure 3 outlines a simplified representation of the cement production process with energy inputs and emission outputs.

Please insert Figure 3 here

[12] United States of America

[13] Including Portland cement, aluminous cement, slag cement, supersulphate cement and similar hydraulic cements: https://comtrade.un.org/data/

[14] According to the European Cement Association: https://cembureau.eu/cement-101/key-facts-figures/

[15] 1 GJ/t = 1 gigajoule per ton = 10^9 joules per ton.

The high energy demand from cement production is mainly due to the heating stage requiring temperatures up to 1600°C due to the endothermic nature of the calcination of calcium carbonate (about 2.80 GJ/t). In addition to the thermal energy, the cement manufacturing process requires electrical power, used in both the materials extraction and mixture crushing.[16] On top of GHG emissions from energy consumption, the decarbonation reaction releases a large amount of CO_2,[17] representing about 60% of cement manufacturing emissions. Finally, the average CO_2 intensity of clinker is about 750kg CO_2/t according to [36] (Figure 3) and accounts for the main contribution to the high overall CO_2 intensity of cement production.

Various means of achieving more environmentally friendly cements are currently in development, including industrial optimisation (energy consumption) and environmental impact mitigation (CO_2 emissions). Some challenges have also been pinpointed upstream of the process. For instance, Kendall et al. [37] linked the optimised production process to local geological and geographical constraints, especially for limestone mining operations in densely populated areas, protected natural areas, and areas with excessive overburden thickness. During cement production, meanwhile, the main options discussed to decrease the environmental impact of the cement industry include increasing energy efficiency, developing carbon capture and storage (CCS), decreasing the clinker to cement ratio, increasing the recycling rate of cement, associating waste heat recovery, and developing the use of alternative fuels[18] [35,37-46]. Potential CO_2 reductions vary greatly from one region to another. At the global level, the IEA cement technology roadmap plots a path to cutting annual CO_2 emissions to 24% below current levels by 2050 through a combination of technology and policy solutions in a 2°C scenario,[19] or a reduction of 32% of the global direct CO_2 intensity of cement [33]. It also recognises the need to consider CO_2 emissions reductions over the overall life cycle of cement, concrete and the built environment (conception and design life of construction for instance) to reduce CO_2 emissions. While reduction potential exists, we will discuss in the data section the limited role of these mitigation actions in reducing cement-related CO_2 emissions for power generation technologies, partly due to the concrete specifications required for the energy sector.

[16] Depending on the technology used, extraction uses between 12 and 15 kWh per ton of mineral extracted, and crushing steps consume around 20-25 kWh per ton of raw materials and 50 to 60 kWh per ton of cement. Overall, each ton of cement produced can use up 80 to 100 kWh of electrical energy (0.29 to 0.36 GJ).

[17] $CaCO_3 \rightarrow CaO + CO_2$: the decomposition of calcium carbonate (limestone) into carbon dioxide and calcium oxide (lime).

[18] The main fuels used for clinker firing are today petroleum coke (used at about 40% of the calorific value consumed), coal and lignite (about 50%), some waste, heavy fuel oil, and gas. Over the past decade, the share of traditional fuels, such as coal, fuel oil and gas, has tended to fall in favour of other more economically attractive fuels, such as petroleum coke, waste, and biomass (including meat and bone meal).

[19] 24% of direct emission reductions, of which 3% due to thermal energy efficiency, 12% to fuel switching, 37% to reducing the clinker cement ratio, and 48% to innovative technologies (including carbon capture); CO_2 reduction linked to heat waste recovery is not included.

3. Methodology

The methodology developed in this article aims to estimate the need for concrete (and therefore cement) to achieve the energy transition objectives in the power sector determined by the IEA climate scenarios. First, we will introduce the structure of the model, before presenting the data considered and finally describing the scenarios used.

3.1 Model structure

In this article, we develop a model with the schematic structure given in Figure 4. The model has as exogenous input data (in red in Figure 4):

- Different power technologies' concrete content.
- CO_2 emissions per ton of cement: this factor varies according to the type of fuel used to supply furnaces with thermal energy. It also has a lower limit due to the intrinsic production of carbon dioxide by the calcination reaction.[20]
- The percentage of cement in concrete: the composition of concrete is generally fixed to meet the appropriate product performance.

The values of these inputs are discussed in part 3.2.

Please insert Figure 4 here

The model's outputs are (in blue in Figure 4):

- The amount of concrete and cement required to develop the electricity sector according to climate scenarios considered.
- The quantity of CO_2 directly emitted to produce this quantity of cement.

The model uses policy scenarios as inputs for the technology mix in the power sector and its evolution over time (in green in Figure 4):

The evolution of installed power capacities is given in 5-year intervals, at global and regional scale. Investments in new installed capacities are dependent on climate objectives and have been derived from the IEA [30] and provided in this article. For accurate results, the lifetime of power plants have also been considered in order to take into account their decommissioning which will impact on future concrete and cement demand. Only considering additional capacities over time, without taking into account technologies' lifespans, leads to underestimating the concrete volumes required. We assume that any technologies with a lifespan of 35 years or less, according to their ages, will be dismantled and potentially replaced once during the period 2014-2050. For technologies with a longer service life, particularly nuclear, decommissioning has been taken into account based on the timetable for nuclear power plants [47]. The hydro technologies have too long lifespan to be dismantled in the 2014-2050

[20] Except if CCS technologies are considered.

period, except for the one built before 1950. Using this methodology, we can evaluate material demand over the period and provide an annual evolution of concrete and cement demand for the power sector.

The cumulative new capacities denoted $NCAP_{r,p}^{cum}$ are then calculated as follows in Eq. 1:

$$NCAP_{r,p}^{cum} = \sum_t NCAP_{r,t,p} = \sum_t \left[\left(CAP_{r,t,p} - CAP_{r,t-1,p} \right) - \left(\sum_{\substack{t'<t \\ \ni \{t-t'<LIFE(r,t',p)\}}} NCAP_{r,t',p} \right) + RCAP_{r,t,p} \right] \quad \text{(Eq. 1)}$$

here:

- t, t' represent the time period over which cumulative installed capacities are calculated. The first period runs from 2014 to 2025, then a 5-year interval is set. t={2014; 2025; 2030; 2035; 2040; 2045; 2050}
  The ∍ symbol means "such that" or "only when" in the equation
- $CAP_{r,t,p}$ represents the installed capacity of the technology *p* at the end of the year *t* in the region *r*,
  and $NCAP_{r,t,p}$ new capacity addition (investment) for technology *p*, in period *t* and region *r*
  $NCAP_{r,p}^{cum}$, the cumulative new installed capacity of the technology *p* in the region *r* during the 2014-2050 period.
- $RCAP_{r,t,p}$ denotes the total amount of capacity that has been retired at period t and periods preceding t of the technology *p* in the region *r*.

Demand from geographical zone *r* at a period *t* for concrete is denoted $D_{r,t}$ and is expressed by Eq. 2:

$$D_{r,t} = \sum_{p \in \{Fossil, Nuclear, Renewables\}} NCAP_{r,t,p} * \alpha_p \quad \text{(Eq. 2)}$$

Where:

- α_p is the concrete content in the technology *p*, expressed in t/MW of new installed capacity.

The resulting demands for cement, water and aggregates, as well as the associated CO_2 emissions, are determined as follows:

$$DMDCement_{r,t} = D_{r,t} * \beta_{cement} \quad \text{(Eq. 3)}$$

$$DMDWater_{r,t} = D_{r,t} * \beta_{water} \quad \text{(Eq. 4)}$$

$$DMDAggregate_{r,t} = D_{r,t} * \beta_{aggregates} \quad \text{(Eq. 5)}$$

$$EmisCO2_{r,t} = DMDCement_{r,t} * \gamma_{cem,t} \quad \text{(Eq. 6)}$$

Where:

- $D_{r,t}$ represents the demand for concrete in the power sector in the geographical area *r* at a period *t*.
- $DMDCement_{r,t}$, $DMDWater_{r,t}$ and $DMDAggregate_{r,t}$ in Eq. 3, 4 and 5 represent the demand for cement, for direct water used in the mixing and batching phase and for the aggregates, respectively at a period *t* in the geographical area *r*.
  β_k represents the proportion of constituent *k* in concrete in weight
- $EmisCO2_{r,t}$, in Eq. 6, represents the direct CO_2 emissions resulting from the production of the cement used in the new installed capacities for power generation sector.
  $\gamma_{cem,t}$ represents the CO_2 quantity emitted per ton of cement produced (CO_2 intensity) at a period *t*

3.2 Data

The lifespan values characterizing the different power generation technologies used to calculate the new capacities, taking into account decommissioning, are given in Table 3.

Please insert Table 3 here

In order to quantify the global impact of concrete used in the power sector, the life-cycle inventory of concrete for each technology has been considered. We examine the life-cycle use of concrete and its components (cement, aggregates, water) throughout the life cycle of each investigated technology per unit of new installed capacity. These inventories are given in Table 1.

The results presented in this article are produced by considering the technological state of the cement and concrete industries. The parameters of the concrete production technology are presented in Table 4.

Please insert Table 4 here

The CO_2 intensity of cement for power generation considered in this study is the world average considered by the IEA. Price-elasticities have been introduced within the IEA ETP-TIMES model for end-use demands, so that demands can react to changes in their prices under a constrained energy system (e.g., under limits or tax on emissions due to climate constraints along with high urbanization growth). The efforts made towards achieving low-carbon cement production which are taken, e.g. improvement of energy efficiency, reduction of clinker-to-cement ratio, alternative binding materials and fuels, etc, would have an impact on its marginal value of production. This elasticity of demand would indicate how much the demand rises/falls in response to a unit change in the marginal cost of meeting a demand that is elastic with a maximum possible variation of demand in both directions when using the elastic demand formulation. The evolution set therefore a cost-effective technology pathway for the cement and concrete industry as recommended by the IEA. The evolution of CO_2 intensity incorporates the greater use of alternative fuels and greater penetration of alternative cement binding materials in order to reduce the clinker-to-cement ratio. They will mitigate the environmental impact of process CO_2 emissions. The cement proportion in the concrete is likely to remain constant in the future to meet the required mechanical and durability properties for different end-use applications. There is no other material currently available that is available in the quantities necessary to meet the demand for buildings and infrastructure. Some alternative cement binding materials that rely on different raw material mixes or different raw materials compared are commercial but in limited quantity i.e. less than 3-5 million tons/yr (e.g. the belite clinker used in the third phase of the three Gorges hydropower project or Calcium sulphoaluminate (CSA) clinker) or at demonstration and pilot phases. Further research in this field could seek to determine the evolution of intra-power generation technologies in order to further narrow the uncertainty about future cement demand and produce a more accurate estimation. Nevertheless, based on our understanding of the different power technologies, average concrete demand could be higher than anticipated in this study due to the development of some renewable-energy-related technologies, such as tower design or foundations of wind turbines requiring more concrete, [25] or evolutionary Generation III nuclear plants[21] [48]. Lastly, no recycling from dismantlement is taken into account in this study and could be part of further analysis due to the fact that supportive strategies which include reusing and recycling concrete in construction among others would certainly be established and strengthened in the coming years by the governments in collaboration with industry.

The major limitation of this work concerning the future environmental impact of concrete production is the aggregation by family type of the power sector technologies when considering material content due to lack of intra-technology representation in all long-term energy system optimization models. this could impact on the concrete and cement demand due to intra-technology structural effect.

3.3 Policy scenario input

The three policy scenarios below defined by the IEA have been considered. They provided this set of scenarios that explore different possible futures, the actions – or inactions – that bring them about and the interconnections between different parts of the entire energy system. These scenarios have been defined at a global and disaggregated in 11 regions (region could be a single country (7 single countries here) such as USA[22], South Africa, China, Mexico, etc. or a group of countries (4 groups) such as European Union, OECD[23], ASEAN[24] or Non-OECD) :

- The RTS or *Reference Technology Scenario* is a scenario that provides a baseline taking into account the energy policies and climate policy commitments of different countries. The RTS

[21] Evolutionary Generation III plants – EPR and Advanced Boiling Water Reactor (ABWR) technologies – use approximately 25% more steel and 70% more concrete than 1970s light-water reactors.

[22] United States of America

[23] Organisation for Economic Co-operation and Development

[24] The Association of Southeast Asian Nations

scenario therefore reflects current climate ambitions, including Nationally Determined Contributions under the Paris Agreement. In the RTS scenario, the share of electricity in final energy demand across all end-use sectors increases (from 18% today to 26% by 2060 in the RTS according to ETP scenarios). Consequently, global electricity demand more than doubles between 2014 and 2060, while CO_2 emissions stabilise after 2030.

- The 2DS scenario is a more ambitious scenario, which translates the climate objective of limiting global warming to 2°C. Energy efficiency is the main factor (after the use of renewables) that contributes to CO_2 emissions reductions (39% of the total CO_2 reduction in comparison with the RTS scenario emissions). This scenario involves also the use of CCS technologies to save 4.2 $GtCO_2$ in 2050 (16% savings).[25] In this scenario, the global power sector reaches net-zero emissions in 2060.
- The B2DS scenario (Beyond 2°C scenario) is a scenario that limits global warming to less than 2°C. It explores how far deployment of technologies already available or in the innovation pipeline could take us beyond the 2DS. Technology improvements and deployment are pushed to their maximum practicable limits across the energy system in order to achieve net-zero emissions by 2060 and to stay net zero or below thereafter. It aims for 1.75°C global warming by 2100. Energy efficiency and CCS technology allow additional savings of 2.5 $GtCO_2$ and 3.1 $GtCO_2$ compared to the 2DS scenario. The global power sector reaches net-zero emissions by 2050 and then becomes net-negative (in particular due to the use of bioenergy with capture carbon and storage).

The power sector has a crucial role to play in achieving these objectives, as it is now the world's largest emitter of carbon dioxide and is growing rapidly worldwide. IEA ETP scenarios describe the changes in the amount of energy produced (Figure 5) and gross installed capacity for the power sector between 2014 and 2050 (Figure 6). There is no information on potential decommissioning included in the latter graph, which represents only the total capacity installed at a given time.

Please insert Figure 5 here

Please insert Figure 6 here

The consequence of switching from the RTS scenario to 2DS or B2DS is that, despite the gradual decrease in the total amount of electricity generated worldwide[26] (Figure 5), there is an overall increase in total gross installed capacity by 2050 (respectively 10% and 17% compared to RTS). This increase is explained by the fact that the energy transition scenarios involve an increase in the share of

[25] https://www.iea.org/etp2017/summary/

[26] Respectively -9.4% and -5.6% in the 2DS and B2DS compared to the RTS, due to the strong innovation hypothesis (especially energy efficiency).

variable renewable energies, whose load factors[27] are on average lower than fossil or nuclear energies (25% for wind onshore, 40% for wind offshore and 15% for PV solar, as opposed to 81% for nuclear, 80% for coal and 35% for natural gas). This difference in the average load factor inevitably requires an increase in the total installed capacity worldwide compared to the RTS scenario at equal quantity of electricity required. The share of fossil-fuel based power generation (oil, coal with or without CCS) obviously decreases strongly in the two most ambitious climate scenarios (2DS and B2DS), while the shares of low carbon technologies (nuclear, hydro, biomass, wind, solar, etc.) become predominant to meet the climate objectives globally. Data are also regionalised, allowing studies at more local scales, showing in particular that marginal abatement efforts can have a major impact on the technology mix of the electricity sector for some regions, as illustrated by the shift from natural gas to onshore wind or biomass and waste between the 2DS and 2BDS scenarios for the ASEAN[28] (Association of Southeast Asian Nations) displayed in Figure 7.

Please insert Figure 7 here

Regional disaggregation and impacts on local cement demand will be discussed in the second part of the results section.

4. Results and discussion

4.1 Global cement demand by 2050 for the power generation sector

Using the ETP data and accounting for decommissioning, based on the lifespan of already-installed technologies, the model allows us to calculate global cumulative new installed capacity between 2014 and 2050 for each climate scenario. In Figure 8, we observe more than 7.5-fold decrease in new coal capacities between RTS and B2DS, while new gas capacities will decrease by almost 55% and new oil capacities will slightly decrease by around 1%. At the same time, the cumulative installed capacities of renewable energy plants (wind, solar, ocean) are expected to increase significantly, by more than 50% and 60% under 2DS and B2DS respectively, compared to RTS levels. Finally, cumulative new installed capacities of nuclear power at the global scale are also expected to increase by almost 65% between B2DS and RTS. Disaggregation between fossil technologies is also necessary due to the difference in their concrete content (very low for natural gas systems even in combined cycle, Table 1). Consequently, the impact of fossil fuel technologies on concrete demand is expected to be lower under B2DS than under RTS, while the opposite result is obtained for renewable and nuclear capacities.

Please insert Figure 8 here

[27] The load factor of a power plant is the ratio between the actual electrical energy produced over a given period and the energy it would have produced had it operated at its rated power during the same period.

[28] Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand and Vietnam.

Based on these results, and the concrete content of each technology used in the above methodology, the model provides concrete, cement, water and aggregates volume demand, as well as total CO_2 emissions due to the cement manufacturing process. The cumulative cement demand in each of the three scenarios, at global level, is given in Table 5. The GHG emissions associated with these production levels are given in the rightmost column. The calculation has been obtained by considering the IEA assumptions where no changes in the clinker-to-cement ratio from 0.65 to 0.66 between 2014 and 2050 in the RTS scenario, while a decrease is considered to 0.6 by 2050 in the 2DS to enable CO2 savings. The thermal energy intensity of clinker (currently 3.5 GJ/t clinker) is reduced to reach by 2050 the global average of 3.2 GJ/t clinker in the RTS scenario and 3.1 GJ/t clinker in the 2DS and B2DS which is close to the reported best available technology performance levels (2.9-3.0 GJ/t clinker for dry-process kilns (ECRA and CSI, 2017; IEA, 2007). The impact of improving the electrical energy efficiency of cement production is offset by the increased electricity demand arising from the use of carbon capture and other carbon emissions mitigation levers. A global average value of electrical energy efficiency has been considered in Table 4 while at a regional level it is varying between 80-116 kWh/ton of cement all around the world (IEA, 2018). The regionalization could then lead to a large differentiation in terms of environmental impacts due to each regional electricity mix.

Please insert Table 5 here

First, we observe an increase in cement demand from the transformation of the power sector for the energy transition. This is true in both ambitious scenarios, as cumulative cement demand increases by 19% and 29% respectively under the 2DS and B2DS scenarios, compared to the RTS scenario. This is the direct consequence of higher cumulative installed capacities with high-concrete-content technologies, such as hydropower or wind power technologies. Without accounting for decommissioning, cement demand was 25 to 30% lower than the results presented in the previous table (Table 5), depending on the scenario. Overall, the cumulative world power sector cement needs by 2050 is assessed between 1130 and 1451 Mt. Therefore they are higher than those obtained by Hertwich et al. [28] who calculated power sector cement needs of 520 Mt by 2050 under the BLUE Map scenario (2010). The difference is explained by a more ambitious global GHG reduction in the 2017 ETP compared to the BLUE map scenario described in the 2010 ETP. Indeed, the BLUE map scenario assumed that global energy-related CO_2 emissions are reduced to half 2005 levels by 2050. In terms of renewable electricity production, the Blue Map scenario is then closer to the current RTS scenario than 2DS or B2DS. Moreover, the importance of the dynamic decommissioning could be pointed out through these results and could therefore lead to rough estimations. Hertwich et al. were assuming decommissioning to amount to 10% of the energy requirements of the construction phase and also, as abovementioned, the material requirements were based on activity and not directly on new installed capacity.

As the global population rises and urbanisation grows, energy transitions will also lead to increasing demand for cement for the power sector, this demand will vary between 40 and 55 Mt by 2050 between the RTS and B2DS scenario, respectively (Figure 9). In the more stringent scenario (B2DS), the power sector cement demand will increase from around 37 Mt in 2025 to almost 55 Mt in 2050. It accounts for a relatively small portion for cement demand as demand projection is assessed to be around 3.9-4.7 billion tons by 2050 [33,49] which is -5% to +19% of the 2017 global cement production level (4.1 billion tons according to the U.S. Geological Survey (USGS) [50]). Consequently, the estimated share of cement allocated to the energy transition for the power generation sector would represent only 1.2-1.5% of world cement production by 2050. The vast majority of the future volume produced is therefore expected to be allocated to improving infrastructure and building housing and factories, for example, in relation to population growth and living conditions improvements. Indeed, according to UN projections [51], 65% of the world's population, or 6.7 billion people, are likely to live in urban areas by 2050 [52]. Cumulative future power sector concrete demand worldwide could thus range between 5.6 and 7.3 billion tons during the period 2014-2050.

Please insert Figure 9 here

Regarding other concrete constituents, the same conclusions can be drawn. The increase in cement demand goes naturally with an increase in demand for both aggregates and water, which remains negligible with respect to global demand (all sectors included). According to our assumptions (Table 4), the cumulative amount of concrete needed for low-carbon electricity generation will require about 4.7 Gt of aggregates under B2DS (around 3.7 Gt under RTS and 4.4 Gt under 2DS), as shown in Table 6. In an annual basis comparison, it will be between 0.66 Gt and 0.88 Gt by 2050 according to the scenarios while world annual construction aggregate demand was around 53 Gt in 2017. Moreover, cumulative direct water consumption needed for mixing and batching in concrete production between 2014 and 2050 is approximately around 848-1088 Mt. According to Miller et al. [53], if production methods remain the same, this water consumption for mixing and batching process represent in average around 15% of the total water consumption on a cradle-to-gate analysis[29]. Therefore, the total cumulative water consumed on a cradle-to-gate for the required concrete for the power generation is estimated at around 5.6-7.3 Gt between 2014 and 2050 (which is equal to 160-210 Mt per year) (Table 6). To put the water consumption from concrete production needed for power generation in perspective, it can be viewed in relation to the total water consumption from concrete production. Miller et al. have estimated that an expected 590–710 Gt of water will be consumed due to concrete production in the next 35 years, if again production methods are assumed to remain the same. Thus, the water consumption from concrete production needed for the building of new capacities in power generation will only represents 0.80-1.25% of the total cumulative water consumed for all concrete produced between 2014 and 2050. Therefore, the water demand for power generation transformation towards the transition to a low-carbon economy will not significantly impact global water stress by

[29] The total water consumption on a cradle-to-gate analysis is the total water consumed associated with cradle-to-gate production of concrete. It represents the water demand from processes and energy flows associated with different phases of manufacturing in concrete production

2050. Nevertheless, considering the quantity of aggregate that is typically locally or regionally sourced, the water demand is clearly a local or regional issue, and can be more challenging at these scales (a point not discussed here).

Please insert Table 6 here

Finally, total CO2 emissions due to power sector demand for cement is expected to decrease by around 46% in 2050 (101 kt in the RTS to 55 kt in the B2DS by 2050). This effort has been possible along with the increasing cement demand through improvement on thermal energy efficiency (the increasing demand for electricity from CCS, due to its growing roll-out, has offset improvements in electrical energy efficiency), reduction of clinker-to-cement ratio, alternative binding materials and fuels. In Table 5, the cumulative CO2 emission is about 594 Mt between 2014 and 2050 in RTS scenario (around 655 Mt under 2DS and 575 Mt under B2DS). A slight increase of the cumulative CO2 emission has been noticed between RTS and 2DS scenarios due to a slight offset between process improvements and energy efficiency measures on the one hand, and increasing cement demand for power sector on the other. In the context of climate policy, this would illustrate the risk of rebound effect with energy efficiency measures that could jeopardize emissions reduction targets. This result holds at the global scale. The next subsection shows however how concrete can have a greater role at the regional level.

4.2 Regional cement demand by 2050 for the power generation sector

While the contribution of the electricity sector to aggregated concrete demand is relatively small, national specificities make concrete more important for the energy transition in some countries than others. Cement and concrete are local markets, so it is difficult to relocate the negative externalities associated with their production. The cement volumes required to implement the new electricity mix by 2050 on a regional scale can therefore be assimilated with future internal production from these regions. This regionalisation is presented in Table 7.

Please insert Table 7 here

The first point of interest is the high consumption of developing countries, where electrification of the economy will increase in the coming decades. This is particularly true for China, India and the ASEAN countries. According to the IEA, electricity production will increase by 67% in China between 2014 and 2050, 332% in India and 246% in ASEAN countries (Figure 10).

Please insert Figure 10 here

The IEA does not provide an Africa vision (South Africa excluded) of the power sector installed capacity through to 2050 in the 2017 ETP, but the continent is also expected to see strong electrification in the medium term.

Focusing on a country level, there are contrasting differences in future cement demand. Surprisingly, China's cement demand will slightly increase between the 3 scenarios considered by 2050 (RTS, 2DS (+5%) or B2DS (+6%)) (Figure 11). Under both 2DS and B2DS, approximately 44% of cement demand is accounted for deployment of hydro technologies. Wind capacities are also partly responsible (about 38%), although their cement content is lower per installed MW. It is important to note that, between 2014 and 2050, the installation of new bioenergy power plant capacity (with or without CCS), hydro and wind technologies, as well as nuclear plants, will account between 87-96% of cement consumption in the power sector from RTS to B2DS scenario. Solar capacities will increase significantly from 806 GW to 1110 GW but will have no impact on cement demand (less than 1% of the cumulative Chinese demand for cement in the more stringent scenario B2DS).

Please insert Figure 11 here

Cement consumption is directly related to the amount of new installed capacities but more importantly to the electricity mix considered. This is illustrated in particular by calculating the cement content of the new installed capacity (in GW) in the different scenarios for a given country (Table 8).

Please insert Table 8 here

Globally, it can be observed that the cement content of new installed capacity in power sector through to 2050 remains relatively stable, from 87 to 89 kt of cement per GW installed. However, it is worth noting that this content varies widely from one region to another, resulting in local carbon intensities linked to this cement production that are significantly higher than the world average. While Mexico has the lowest cement intensity in power mix (45 kt/GW in B2DS), Brazil has the highest (160 kt/GW, B2DS), followed by Russia (155 kt/GW, B2DS) and the ASEAN countries (111 kt/GW, B2DS), with relatively high-emission mixes compared to cement demand. The US also stands out for the low cement content of its new electricity mix (51 kt/GW). These differences can be explained by power generation technology choices. Mexico and the US will have considerable solar capacities (PV or CSP) by 2050, while Brazil will have significant installed hydropower capacities.

The second point to consider is that cement intensities can vary positively or negatively within the same geographical area, depending on the scenario considered. In Russia for example, there is a 34% increase in cement consumption per installed GW between the RTS and B2DS scenarios, while in Brazil there is a 8% reduction. The electricity mixes of these two countries are shown in Figure 12.

Please insert Figure 12 here

For Russia, the cement content (and corresponding CO_2 intensity) of the average new installed electrical power capacity is higher under B2DS than RTS due to new hydropower capacities (+64 to 85% of installed GW compared to RTS) and onshore wind (+494 to 582% compared to RTS) which require large volumes of concrete. Conversely, Brazil's CO_2 intensity decreases from 92 kt CO_2/GW to 65 kt CO_2/GW due to the development of energy technologies with lower concrete content (solar PV in particular) along with a lower CO2 power sector intensity due to the roll-out of bioenergy, hydro, nuclear and wind plants. Total cement demand does however remain relatively stable between the three Brazilian scenarios, concrete content reductions being offset in both climate scenarios by the installation of additional capacities.

We have therefore just illustrated the regional disparities in cement demand for future power mixes based on the ETP 2017 scenarios. In the previous section, it has been shown that the cement volumes required globally for the energy transition in the electricity sector were low.

The large Chinese cement volumes mask in reality a local disparity, when the results are considered on a global scale. Cement volumes required for the future power sector are considerable in the rest of the world given current cement volume production and capacities, especially in other emerging countries such as Brazil, India or Russia. In Africa, demand for cement for the construction of power plants, while not quantified, could also represent a major challenge. Given the continent's urbanisation rate (the highest in the world) and growing population, this issue should be taken seriously. The African cement industry is expanding rapidly, especially in countries such as Ethiopia, Nigeria, and Tanzania.[30] However, the presence of a single predominant actor on the market (Dangote, which represents more than 35% of the continent's cement production, or about 45 Mt) and the capital intensity of the cement industry (usually above $175M per million tonnes of annual capacity, equivalent to around 3 years of turnover[31]), as well as transport costs and the high energy intensity of the process, will make significant development of this industry to meet future cement demand in the African power and building sectors challenging.

Both in Africa and in India, another issue for the cement industry relates to "power availability", concerning problems such as power cuts, fuel shortages, inadequate availability of wagons for transport and limited availability of furnaces. In India, about 65% of electricity requirements for cement manufacture are met through coal plants installed at cement manufacturing facilities to reduce energy costs and ensure steady power availability. The Indian cement industry has nearly 4,000 MW of installed captive (i.e. dedicated to the cement plant) power capacity, including coal-based plants as well as diesel generators and wind turbines to overcome rising power costs and supply uncertainty. Captive power plants will continue to grow as long as steady and continuous grid power is not available at a competitive cost. However, this represents an additional cost for new cement plant projects. In addition, cement plants in Africa and in India often have higher CO_2 intensities than elsewhere. In India, overall CO_2 emissions total 866 kg/ton of clinker produced. The IEA has

[30] https://www.bloomberg.com/professional/blog/africas-cement-industry-is-expanding-fast/

[31] The European Cement Association – Key Facts & Figures

estimated the additional investment required to reduce the Indian cement industry's CO_2-emission growth by 2050 at between $34 and $100 billion, or 20 to 30% higher than under a business-as-usual scenario [54].

5. Concluding remarks

In this article, future demand for concrete and cement has been quantified. By studying different energy transition scenarios, the cement manufacturing process and the concrete requirements of power plants, we show that cumulative cement demand for the power generation sector over the 2014-2050 period will not exceed 1.5 Gt. There is a global increase in cement demand in the power sector in response to the energy transition (+19 or 29% for 2DS and B2DS compared to RTS). However, even under the most stringent scenario (B2DS), the volume of cement required by 2050 would represent only about 1.2-1.5% of 2050 world cement production. Therefore, it seems unlikely that the development of the power sector will contribute substantially to a significant shortage of cement or specific environmental externalities.

At the local level, there is high cement consumption in developing countries, where electrification of the economy will increase in the coming decades and lead to high growth in total electricity consumption (as in India). While cement consumption is of course directly related to the volume of new installed capacities, it is mostly a consequence of the future electricity mix. At the global level, the cement content of power generation technologies up 2050 should remain stable, while it is significantly higher in some regions and countries (such as Russia, the ASEAN and Brazil). Cement is in some cases an important material for the energy transition in the electricity sector (especially in places where hydro, wind or nuclear power plants are more developed, while it is used less in other electricity mixes such as those using solar). As cement production is highly CO_2-emitting and difficult to relocate, national policies need to implement systemic GHG-emission mitigation measures in all sectors of the economy (industry, power, etc.) in order to ensure that their overall climate policy is consistent with ambitious reduction targets. Finally, we have also found that, while the volume of cement required globally for the electricity sector is negligible compared to cement production, it can represent a significant part of local production (particularly in developing areas such as Africa, India, Brazil or Russia, and in the USA). This last result demonstrates the importance of forecasting how the energy transition can increase the risk of bottlenecks in material production, even for materials such as cement that are not considered to be critical.

In the future, sensitivity analyses could be conducted, using our model to investigate, for example, the impact of a reduction in CO_2 emissions from the production process, especially at the regional level, to check compatibility with local climate policies in terms of GHG emissions (especially with Nationally Determined Contributions). Given that some regions may be more prone to water stress associated with concrete production, more in-depth analyses of the water demand required for power sector transition may be relevant on a regional scale. Our outcomes could also be the basis for analysis of crediting mechanisms in developing and developed countries such as the Clean Development Mechanism (CDM) or Joint Implementation (JI), in order to encourage investments in emissions reductions where they are least expensive. In other words, the outcomes of our model could be useful for policy makers to transform current concepts of sectorial agreements into effective international policy instruments that will promote the rapid and cost-effective deployment of the best available technologies (BATs) and innovation. More extensively, an analysis of a global carbon tax could assess potential competitiveness in different world regions under IEA scenarios and thus also encourage trade to pool emissions-mitigation efforts.

Finally, the energy transition could certainly have a great impact on demand for certain other materials, as Renewable Energy Technologies (RETs) and fossil-based technologies in the power sector require large amounts of minerals. The analysis of demand for other raw materials depending on the future uncertainty of power sector development under IEA scenarios could also be an asset for further research.

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