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To cite this version:

Vivien Fisch-Romito. Embodied carbon dioxide emissions to provide high access levels to basic infrastructure around the world. Global Environmental Change, 2021, 70, pp.102362. 10.1016/j.gloenvcha.2021.102362 . hal-03353919

Embodied carbon dioxide emissions to provide universal high levels of access to basic infrastructure

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Acknowledgements

I thank Céline Guivarch, Meriem Hamdi-Cherif and audiences at the ISIE-SEM 2019 and IEW 2019 conferences for useful comments and suggestions on previous versions of this paper.

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Embodied carbon dioxide emissions to provide universal high levels of access to basic infrastructure

Abstract

Access to infrastructure services is essential to meet human basic needs. However, infrastructure construction requires carbon-intensive materials, first and foremost cement and steel. In this paper, I assess if high level of access to 5 basic infrastructure services - electricity, water, shelter, sanitation and transportation - can be provided at the global scale in 2030 and until 2050 without compromising climate mitigation targets. Following historical patterns, I first quantify the cement and steel requirements in each country associated with providing high access levels. I then estimate the production-based carbon dioxide emissions related to manufacturing the cement and steel needs. To do so, I model influencing factors such as national production technologies mix, trade structure and mitigation actions in the cement and steel industries. Global cumulative material demand (central values) to reach high access level in 2030 is the lowest for water with 8 Gt of cement and 1 Gt of steel and the highest for transportation with 50 Gt of cement and 6 Gt of steel. Most of the cement and steel demand is concentrated in Asia, Middle-East and Africa. I show for all infrastructure services that achieving high access level in 2030 and until 2050 induces cumulative carbon dioxide emissions well below the carbon budgets related to Paris Agreement targets, with central values under baseline scenario from 10 to 53 Gt CO_2 depending on the infrastructure service. However, I find providing high sanitation and transportation access in Middle-East and Africa conflicts with existing low-carbon pathways. This calls for on one side implementing material efficiency and substitution towards less carbon-intensive construction materials, and on the other side strengthening mitigation efforts in wealthiest countries to leave enough 'carbon space' for basic infrastructure development in emerging countries.

Keywords— basic needs; infrastructure access; embodied carbon dioxide emissions

1 Introduction

Human societies face the challenge of increasing well-being while limiting impact on the climate. Assessing the relationship between human well-being and carbon emissions or energy consumption is crucial to highlight the (un)consistencies between mitigating climate change and providing a high quality of life for all. Since human well-being differ from economic affluence (Roberts *et al.*, 2020) and GDP is a limited indicator to represent social progress (Stiglitz *et al.*, 2009), indicators beyond GDP or incomes should be used to measure well-being.

Different metrics have been applied to investigate empirically the link between human development and energy or carbon footprint. Some authors have used life expectancy whereas others have used composite indicators such as the Human Development Index (HDI) to integrate the multidimensional aspect of human well-being (Kahneman & Krueger, 2006). All these studies have found non linear-relationship with a high correlation between energy consumption or carbon emissions and well-being at low level of well-being but not at high level (Ribas *et al.*, 2019; Lamb *et al.*, 2014; Jorgenson, 2014; Costa *et al.*, 2011; Steinberger & Roberts, 2010).

Using composite indicators is however problematic because it implies a substitutability between the dimensions and requires to assign weights to them (Decancq & Lugo, 2013). Doyal & Gough (1991) and Max-Neef *et al.* (1992) have proposed a set of universal human needs to fulfill. In the human needs theories, needs are plural, non-substitutable, satiable, cross-generational and universal but the way to satisfy them (need satisfiers) can differ between regions such as the type of food or dwelling. Doyal & Gough (1991) distinguished two basic needs-personal autonomy and health- that depend on other intermediate needs such as security in childhood or clean water. Gough (2015) updated this analytical framework and highlighted the need to define 'sufficient' levels for human needs regarding the environmental constraint.

The human needs approach has permeated the climate change mitigation literature trough different concepts to quantify the energy or carbon emissions associated with basic needs satisfaction : the Subsistence Emissions (Shue, 1993), the Decent Living Emissions (Rao & Baer, 2012) or the ‘Safe and Just Operating Space ’(so-called ‘Doughnut’) (Raworth, 2012). It is also reflected in the Sustainable Development Goals agenda containing 17 goals and 169 targets (United Nations, 2015).

Infrastructure such as buildings and civil engineering networks influences the achievement of many development goals either directly or indirectly (Thacker *et al.*, 2019). This pivotal role is evident for the SDG 9-*Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.* Infrastructure stock is one of the factors explaining economic growth (Calderón & Servén, 2004; Straub, 2011) and hence contributes to the achievement of the SGD 8 - *Promote inclusive and sustainable economic growth, employment and decent work for all.* It is also a determinant of poverty reduction (Akanbi, 2015; Ogun, 2010) which is essential for the SGD1-*End poverty in all it forms everywhere.* Infrastructure is an instrument to provide essential services to meet human needs (Steckel *et al.*, 2017; Clark *et al.*, 2018) such as water, sanitation or transport. However, access to basic infrastructures varies widely among countries even when incomes are similar (Steckel *et al.*, 2017).

Yet, manufacturing the construction materials required for infrastructure is an important source of greenhouse gas emissions. The emissions embodied in materials account for over 90% of lifecycle emissions in infrastructures (Huang *et al.*, 2018) and emissions from the construction of new urban infrastructure could represent 27.5% of total urban emissions between 2016 and 2030 (Creutzig *et al.*, 2016). Mitigating these embodied emissions are crucial to reach carbon neutrality.

Most of the embodied emissions come from cement and steel productions, which are CO_2 intensive industries. These two core materials are used in all countries at any development stage for construction, the other construction materials such as aluminium and cooper being specific to more advanced applications (Bleischwitz *et al.*, 2018). In 2014, the steel and cement industries accounted for 5.8% and 5.6% of global CO_2 emissions respectively (IEA, 2017b).

Their contribution to global CO_2 emissions is expected to continue in the short-term for two reasons. First of all, process emissions resulting from chemical reactions involved to manufacture materials are difficult to eliminate without carbon capture and storage technologies (Davis *et al.*, 2018). Secondly, the technical lifetimes of the capital used in the heavy industries are between 30 and 40 years, creating inertia in the renewal of technologies and slowing possibilities to reduce emissions (Erickson *et al.*, 2015). A rapid increase of the global infrastructure stock in the short term could then consume a significant part of the carbon budget available to meet the Paris Agreement targets (Krausmann *et al.*, 2020; Müller *et al.*, 2013).

In this paper, I ask if high level of access to basic infrastructure services can be provided at the global scale in 2030 without compromising climate mitigation targets. I analyse how the access rates evolve with the increase of infrastructure stock and construction materials consumption and how much construction materials and CO_2 emissions are associated with providing high infrastructure access.

A first literature strand has assessed the energy needs and carbon impact of providing high access levels to different infrastructure services but without considering the embodied CO_2 emissions in construction materials. Some studies have estimated the CO_2 emissions from final energy use to expand energy access and have found a small contribution to global warming (Chakravarty & Tavoni, 2013; Pachauri *et al.*, 2013, 2014). Other studies have analysed empirically the relationship between GHG emissions or energy consumption - all sectors aggregated - and access levels to basic infrastructure such as water, sanitation or electricity (Rao *et al.*, 2014; Lamb & Rao, 2015; O'Neill *et al.*, 2018). They have highlighted the best fit curves are either linear-logarithmic or saturation curves. This suggests that after a certain threshold of access, a low increase of access level is associated with a high carbon impact. Lamb & Rao (2015) and O'Neill *et al.* (2018) have also projected the system-wide carbon emissions associated with the achievement of high access rates to sanitation, electricity or water but only in pathways unconstrained by mitigation actions.

Another literature strand has projected the energy consumption and CO_2 emissions from cement and steel sectors but without considering whether or not infrastructure access needs were provided. Several studies have used econometric relationship between cement or steel production and GDP (Zhang *et al.*, 2018; van Ruijven *et al.*, 2016; Steckel *et al.*, 2013). Among them, Steckel *et al.* (2013) suggested a potential tension between energy consumption decrease in existing scenarios and the energy necessary for infrastructure build-up. Other studies from industrial ecology field have used the concept of in-use material stock to link the increase of infrastructure and the material flows required (and the associated embodied emissions) to build it up (Pauliuk *et al.*, 2017; Chen & Haynes, 2015). Müller *et al.* (2013) showed an extension at the global scale of wealthiest countries' in-use stock levels for cement, steel and aluminium would consume a significant part of the carbon budget available to stay below 2°C. Although, the convergence of developing countries to infrastructure level of wealthiest countries would be associated with higher access level to basic infrastructures, this objective is questionable because of potential negative outcomes such as land take (Colsaet *et al.*, 2018) and it could not induce significant progress for countries with already high access rates (O'Neill *et al.*, 2018; Rao *et al.*, 2014). Krausmann *et al.* (2020) has recently estimated the embodied CO_2 emissions - all materials considered - for a global convergence at the per-capita level of in-use stocks that the developed countries had achieved in 1970, considering it as 'sufficient' in terms of life quality. Authors highlighted large reductions in global resource demand and emissions compared to the scenario where countries converge to the current infrastructure level of industrialized countries.

Few studies have focused on the carbon/energy embodied in construction materials to provide access to basic infrastructure. Two studies have bottom-up estimated using life cycle analysis and input-output tools the energy needs - including the energy used in building some basic infrastructure - to provide decent material living standards to the full population in three countries (Rao *et al.*, 2019) and at the global scale (Millward-Hopkins *et al.*, 2020). Wenz *et al.* (2020) quantified the cumulative embodied CO_2 emissions associated with building global road network to provide universal access to road.

In this paper, I first use historical data to describe the global trends of access to 5 basic infrastructure services - electricity, water, sanitation, shelter or transport - in relation to the steel and cement embodied in infrastructure stocks. Then, following historical patterns, I quantify the amounts of cement and steel needed in each country associated with reaching high access levels in 2030 and kept access levels high until 2050 for each of the infrastructure services. Finally, I estimate the cumulative $C0_2$ emissions from manufacturing cement and steel requirements. I discuss my findings with respect to the available carbon budgets and the existing scenarios of material production and greenhouse gas emissions in the cement and steel industries.

This study goes beyond the existing literature in different aspects. First, I assess the material and carbon impact of achieving 5 sustainable development goals related to infrastructure access. Then, I take into account country-specific determinants of cement and steel consumption such as trade structure and carbon intensity of material production to calculate production-based CO_2 emissions. Finally, I use 3 decarbonization scenarios of the cement and steel industries (i)to assess how the projected low-carbon transition in these industries limits the carbon impact of providing infrastructure access and (ii) to disentangle the contributions to emissions pathways from changes in the carbon intensities of material production and in the material demands.

The rest of this article is structured as follows: Section 2 describes the methodology, Section 3 presents the results and discussion and Section 4 provides a summary and a conclusion.

2 Methodology

In a first step, I used historical data to quantify the cement and steel consumption for each country to provide high access levels to different infrastructure services in 2030 and until 2050 in case of population changes. Subsection 2.1 describes the data and the global historical patterns of infrastructure access along the material stocks increase. Subsection 2.2 details the modelling approach used in this step. In a second step, I quantified the CO_2 emissions corresponding to the material consumptions obtained in the previous step. Subsection 2.3 describes how I represented in the modelling framework country-specific determinants of CO_2 emissions related to cement and steel consumption.

2.1 Analysing trends in infrastructure access levels along the in-use material stocks build-up

2.1.1 Data and definitions

I chose to focus on 5 basic infrastructure services - water, electricity, shelter, sanitation and transportation. In the human needs theory, they are essential needs satisfiers contributing through different channels to personal autonomy and physical health (Gough, 2015). Access definition is more straightforward than other infrastructure services such as health or education (Steckel *et al.*, 2017) and data are available over several years and countries (Table 1). The infrastructure associated is capital-intensive and requires cement and steel (see Du Fei *et al.* (2013) for water and sanitation systems, Anastasiou *et al.* (2015) for road network or Bumby *et al.* (2010) for power distribution).

Different indicators of access are available in the literature for each infrastructure service. For instance, for transportation access, researchers have used in the literature the Rural Access Index (Iimi *et al.*, 2016) defined as the proportion of population living within 2 km of an all-season road, the travel time required to reach the nearest urban centre (Weiss *et al.*, 2018) or the share of paved roads (Jakob *et al.*, 2016). I privileged the official indicators used to assess sustainable development goals progress or those closest to, depending on data availability (Table 1). The complete list of indicators used in the SDGs is available at `https://unstats.un.org/sdgs/indicators/indicators-list/`.

Electricity access contributes to physical health by reducing indoor air pollution through replacing biomass fuels and coals (Duflo *et al.*, 2008). It is related to the SDG 7.1 "*Universal access to affordable, reliable and modern energy services*". I used the official SDG indicator being defined as the percentage of population having access to household electricity.

At least 50 litres per person per day are needed to ensure hygiene including laundry and domestic cleaning. Inadequate access to safe drinking water is associated with diarrhoea disease and exposure to chemical pollutants (Hunter *et al.*, 2010). This is related to the SDG 6.1 "*Universal and equitable access to safe and affordable drinking water for all*". The official indicator is the percentage of people using safely managed drinking water services. I used the percentage of population having access to an improved water source such as piped household water, public tap, tube well/borehole, protected dug wells, protected springs or rainwater collection. This indicator is close in definition to the official one and has better geographical and temporal coverages.

Sanitation access contributes to physical health, lack of access being a risk factor child health facilitating fecal-oral transmissions of pathogens and causing various diarrheal disease (Larsen *et al.*, 2017). It corresponds to the SDG 6.2 "*Access to adequate and equitable sanitation and hygiene for all and end open defecation*". The official indicator is the proportion of population using safely managed sanitation services. I used the percentage of population having access to improved sanitation facilities included flush/pour flush (to piped sewer system, septic tank, pit latrine), ventilated improved pit latrine, pit latrine with slab, and composting toilet. This indicator is close in definition and has better temporal and geographical coverages.

Shelter access indicator is defined as the proportion of urban population that does not live in slum household. A slum household is considered here as a group of individuals living under the same roof lacking one or more of the following conditions: access to improved water, access to improved sanitation, sufficient living area, and durability of housing. It is the official indicator of the SDG 11.1 "*Ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums*".

Transportation accessibility contributes to personal autonomy, and has an impact on employment (Johnson *et al.*, 2017) and leisures participation (Kessides, 1993). It can be linked to the SDG 9.1 "*Develop quality, reliable, sustainable and resilient infrastructure, including regional and trans-border infrastructure*". The official indicator associated is the Rural Access Index (RAI) defined as the proportion of the rural population living within 2 km of an all-season road. Although mobility can also take place by rail, this indicator can be considered as a proxy for transportation accessibility by assuming that railway lines are mostly doubled with roads. I modified this indicator to get the share of the overall population living within 2 km of an all season road using urbanization rate data, assuming all urban inhabitants live within 2 km of an all-season road.

I aim to relate the cement and steel materials consumption to the access to infrastructure services. However, linear meters of infrastructure and construction materials used are not available at the country scale and for each infrastructure service. I therefore based the analysis on data of in-use stocks of cement and steel which are the amounts of steel and cement contained in the installed capital stocks (Chen & Haynes, 2015). Researchers have characterized historical patterns of cement and steel stocks tracking the different flows and stock dynamics and taking into account the capital lifetime containing the material. Data and sources for in-use material stocks are synthesized in Table 2. I describe in the next subsection the methodology to break down the stock estimates into the different service categories. Although also contributing to basic needs, I did not consider in this study the steel contained in basic appliances or vehicles. Including these categories goes beyond the scope of this article as they are mobile stock and not infrastructure (Lanau *et al.*, 2019). It would also imply heavy hypothesis at the regional scale on life duration and recycling rate on the time period studied.

2.1.2 Patterns of infrastructure access

Literature mentioned non-linear functional forms such as the semi-logarithmic or the hyperbolic curves (O'Neill *et al.*, 2018; Lamb & Rao, 2015; Rao *et al.*, 2014) as relevant to characterize relationships between infrastructure access and environmental impact. In the same manner, the scatter plots of each infrastructures access-material stock pair (figure 1) suggest a correlation between these variables following a non-linear trend. It indicates that, from a certain access threshold and before reaching full access, a small increase of access rate is associated with a high increase of infrastructure stocks and construction material needs.

I estimated the in-use material stock levels per capita contained in the whole infrastructure stock that are consistent with high access level for each infrastructure service. I first defined as high access level a percentage of the population in each country having access to an infrastructure service. I recognize this process is normative. Even though in the SDG framework universal access to infrastructure services is targeted, some indicators are today below 100% in the wealthiest countries for transportation or sanitation access. I hence considered the level of 90% as target following Lamb (2016) and Rao *et al.* (2014). I also tested the 95% value for illustrative purpose and to show the sensitivity of the results to a higher coverage level.

Following O'Neill *et al.* (2018), I selected for each infrastructure service the 20 country-year observations where access rates were closest to the access threshold targeted (90% or 95%) and then extracted the values of per capita in-use stocks of cement and steel. The 20 values sample allows to get a representative subset of the points closest to the access threshold without deviating too far from it. For each country, I only kept the observation with the access rate closest to the access threshold targeted so that a country's own performance does not unduly influence the overall result. Since transportation access data was available only for the year 2014, I projected steel stock values from 2008 to 2014, assuming that the ratio of the cement stock growth rate to the steel stock growth rate was the same as the 2005-2008 period for each country. I then identified the distribution and the median value of material stocks per capita on this subsample and compared them according to the infrastructure or material considered.

These values represent the materials embodied in the whole infrastructure stock. They should not be considered as materials used specifically for one infrastructure type but rather as the construction material intensity of the economic system to provide access to an infrastructure type.

Figure 2 presents the distribution of in-use cement and steel stocks per capita for the 20 countries with the access level closest to 90%. The median values differ between infrastructure type and materials to achieve high access rates. Values are higher for cement than steel for all infrastructures considered, with a factor ranging from 6 for water to 12 for shelter. While the lowest values obtained are for electricity with 4.53 tons of cement per capita and 0.46 ton of steel per capita, these values are the highest for transportation reaching respectively 13.08 tons of cement per capita and 1.75 ton of steel per capita. Infrastructure access tends to follow a sequencing process along material stocks increase with electricity and water coming first, and transport access last, which is in line with previous results (Steckel *et al.*, 2017). For the year 2014, only 10 countries reach an access rate to sanitation services without having done the same for either electricity or water. 8 countries reach an access rate to transportation higher than 90% without having done the same on one of the other infrastructure.

2.2 Estimating the cement and steel requirements in each country to reach high infrastructure access

The global median values of in-use material stocks per capita associated with high infrastructure access, obtained in the last section, may seem plausible as targets for developing countries. However, some countries have already reached the access level of 90% on some infrastructure for lower values of in-use material stocks per capita. Conversely, other countries have not yet reached the access level of 90% on some infrastructures for higher values of in-use material stocks per capita. Country specific determinants such as the urbanization level or spatial organization affect the cement and steel consumption in each country when economic development levels are similar. Higher urban density decrease the materials stocked in networked infrastructures but increase the structural material stock contained in buildings because of greater height (Norman *et al.*, 2006; Schiller, 2007). Construction techniques and materials used can also differ between countries. Explicitly integrating the influence of these parameters goes beyond the scope of this study and could be done in further research.

I hence refined the median estimation approach to represent partially country specific patterns of cement and steel consumption and to represent two stylized facts observed in the literature about cement and steel in-use stocks : (i) cement and steel stocks per capita increase during the development process before saturating or decreasing for wealthiest countries and (ii) material stocks are immobile for many decades and will not decrease in the short term (Cao *et al.*, 2017; Bleischwitz *et al.*, 2018). I considered different conditional cases summarized in the table 3 to allocate to each country and for each infrastructure service a level of in-use materials stocks per capita to reach for providing high access. The way in which the different cases are constructed gives rather lower bound of in-use stocks to target. I also performed the same analysis replacing the global median value by the first and the third quartiles of the distributions obtained in the previous methodology step to integrate uncertainties. This approach is also relevant to limit the discontinuities effects induced by the different conditional case for countries with access rates close to 90% or in-use stock per capita close to the global median value.

I then estimated the cement and steel needs to reach in 2030 the in-use stocks per capita targeted in 2030 and to keep it at this value until 2050 in case of population increase. As mentioned before, I used as targets overall infrastructure system-wide material stock values consistent with high access level for each infrastructure service. The target values I obtained can't be added to avoid double counting. I could also have used as target a single value of material stock per capita based only on countries that had access to all infrastructure services. However, I rather chose to analyse each infrastructure services independently in order to highlight those where a high access target in the short term is consistent or inconsistent with low-carbon trajectories.

I did not integrate capital depreciation here so the material needs obtained should be considered as lower bounds. I used national population projection from the Shared Socioeconomic Pathway 2 (SSP2) scenario (O'Neill *et al.*, 2017). It is a medium scenario with global population increasing from 6.9 billion people in 2005 to more than 9 billion people in 2050 (Kc & Lutz, 2017). Using this population scenario also allows to compare my quantifications of material needs and carbon emissions with the literature. I assumed linear evolution of national in-use material stock towards targeted stock.

2.3 Quantifying the production-based CO_2 emissions related to manufacturing cement and steel

In this section, I detail the modelling choices for calculating the production-based CO_2 emissions induced by cement and steel requirements in each country, obtained in the previous step.

2.3.1 Steel production

The steel production is today mainly divided into two production routes, the blast furnace-basic oxygen furnace (BF-BOF) and the electric arc furnace (EAF). In the conventional BF-BOF route, iron ore and coke are melted in a blast furnace in order to reduce iron ore and obtain pig iron. The latter is then converted to steel in the basic oxygen furnace. Instead of using BOF, iron can also be refined into steel in an open hearth furnace (OHF) but this technology is energy intensive and is used to a smaller extent (World Steel Association, 2016). Electric arc furnace steelmaking uses scrap steel as the main feed material. Direct reduced iron (DRI) can also be used in electric arc furnace, the iron ore being reduced by a gas produced from natural gas or coal.

The four steel production routes (BF-BOF, BF-OHF, scrap-EAF and DRI-EAF) differ in terms of energy consumption and CO_2 emissions (Morfeldt *et al.*, 2015). I synthesised in Table 4 the related direct CO_2 emissions and the electricity consumption. I considered here emissions from raw material preparation processes (sintering and coking) to rolling processes using mill to be consistent with the decarbonisation scenarios of the steel sector I used (see subsection 2.3.4).

For each steel producing country, I calculated the technology weighted average emissions for one ton of steel produced. Doing so, I assumed possible substitution between scrap-based steel and steel produced from virgin materials, following (Morfeldt *et al.*, 2015) and (Milford *et al.*, 2013). National production routes shares for the year 2015 were obtained from World

Steel Association (2016) and grid carbon intensity for the year 2015 from IEA (2017a). When value were unavailable for a country, I applied the global average technology mix or the global average value of grid carbon intensity. Data and sources are synthesized in table 5.

The calibration is consistent with previous estimations. Hasanbeigi *et al.* (2016) obtained for the year 2010 CO_2 emissions intensity of production equal to 2.15 t CO_2/ton steel for China, 1.71 t CO_2/t steel for Germany, 1.08 t CO_2/t steel for Mexico, and 1.74 t CO_2/t steel for U.S.A. My corresponding calibrated values are respectively 2.19, 1.73, 1.40 and 1.12 tCO2/t steel. This suggests a change in the technology used to produce steel in Mexico and U.S.A. from 2010.

2.3.2 Cement production

Cement manufacturing can be separated into two distinct stages. The first stage is producing clinker by limestone calcination reaction in a rotating kiln. This chemical reaction releases CO_2 in itself, which is referred to here as process emissions. Process emissions represent the major part of cement emissions and depend on the amount of clinker contained in one ton of cement, which varies between regions and over time (Kermeli *et al.*, 2019; Andrew, 2018).

The direct CO_2 emissions come from the combustion of fossil fuels to heat the kiln and depend on the energy intensity of the kiln system and the carbon intensity of the fuel used. Clinker can be produced in wet, dry, semi-dry or semi-wet kilns depending on the moisture content of raw materials. The dry process is the most energy efficient kiln technology and is the most used one. The reduction of emissions in the cement sector is more related to a change in technological level than to a choice of production route as in the steel sector (van Ruijven *et al.*, 2016).

The second production stage is the blending and grinding of clinker with other materials to produce cement (Branger & Sato, 2017). The conversion of primary energy into electricity used during this process also generates CO_2 emissions, which I refer to as indirect emissions.

I estimated process, direct and indirect emissions to produce one ton of cement in each cement producing country. The World Business Council for Sustainable Development (WBCSD) developed the Getting the Numbers Right (GNR) database synthesizing from 2005 to 2018 technical informations for more than 900 individual cement plants in different world regions. I extracted for the year 2015 the regional average values of clinker ratio, carbon intensity of the fuel mix, thermal energy consumption and cement plant power consumption (WBCSD, 2016). I applied these values to each countries included in the related world regions. Process emissions factor for clinker production was taken from Eggleston *et al.* (2006) and national CO2 intensity of grid from IEA (2017a). Data and sources are synthesized in table 5.

2.3.3 Trade structure

I aim to calculate producing-based CO_2 emissions to be able to compare the results with national or regional carbon budgets. This calls for representing in the modelling framework the trade structure to allocate CO_2 emissions to the producing countries for each ton of cement and steel used in a given country. The trade ratio - the ratio of traded products weight and global production weight - highlights which materials are particularly concerned by trade flow and imported or exported emissions. For pig iron, an intermediate product of steel manufacturing, the trade ratio was 8% in 2015 (World Steel Association, 2016) and for cement products 5% (UNSD, 2018; Van Oss, 2016). Cement is a commodity consumed mostly locally because of high transportation costs (Cao *et al.*, 2017). I assumed the related trade effects associated on emissions for these products are negligible. I considered here one ton of cement produced in a country is consumed in the same one following Hache *et al.* (2020) and Denis-Ryan *et al.* (2016).

Conversely, the 2015 value of trade ratio for crude steel is 30% highlighting potential imported or exported emissions. To represent the steel trade structure, I first extracted from BACI database (Gaulier & Zignago, 2010) the imports and exports flows in weight of steel primary products for the year 2015 and for 207 countries. The commodity HS codes considered are from 7206 to 7306 following the World Steel Association guidelines (World Steel Association, 2011). I then summed all the steel flows from one country to another and built a bilateral trade matrix where each element (i,j) represent the aggregated weight of steel primary products imported by the country i from the country j. I then incorporated in the matrix diagonal the domestic consumption assuming it as equal to the steel production minus the steel exports (in case of negative values, it was considered as null). I finally divided each line i by the apparent consumption - domestic production minus exports plus imports - of the country i. Steel production data was obtained from World Steel Association (2016). In each cell (i,j), the obtained value represents the share of country i consumption of steel primary products coming from the country j.

2.3.4 Scenarii used for the dynamics of the production-based emissions determinants

I considered 3 alternative scenarios - *baseline*, *median2C*, *below2C* - to project the evolution of carbon intensity for cement and steel production, and grid (table 6). My goals are to (i) analyse how the projected low-carbon transition in these industries limits the carbon impact of providing basic infrastructure access and (ii) to disentangle the contributions to emissions pathways from changes in the carbon intensity of materials production and in the materials demand.

In the baseline scenario, all the parameters are assumed constant. I assumed the steel trade structure as constant for all scenarios but alternatives could be done which will change the allocation of producing-based CO_2 emissions. Carbon intensities of production values in 2030 and 2050 are based on the 2°C (2DS) and the Beyond 2°C (B2DS) scenarios trajectory (IEA, 2017b, 2018) for respectively the *median2C* and the *below2C* alternatives. The 2DS scenarios refers to a CO_2 emissions trajectory consistent with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100, with cumulative emissions of 1 170 Gt CO_2 between 2015 and 2100. The B2DS cumulative emissions from the energy sector of around 750 Gt CO_2 between 2015 and 2100, which is consistent with a 50% chance of limiting average future temperature increases to 1.75°C. The emissions reduction relies on using best available technologies to improve overall energy efficiency and deploying CO_2 capture technologies. It also implies for steel production to increase the global share of steel production for EAF route- both from scrap-based and DRI-based- to more than 50% and for cement production to decrease the clinker ratio. I assumed for all countries a linear evolution of carbon intensity from 2015 to 2030 and from 2030 to 2050.

To project the evolution of the carbon intensity of electricity, I use the average values in 2050 extracted from the low carbon scenario database ADVANCE (Luderer *et al.*, 2018; Vrontisi *et al.*, 2018), which is described in more detail in the next section. Data are disaggregated across 5 major world regions and for different levels of climate ambition. Following Audoly *et al.* (2018), I defined the carbon content of electricity as the ratio between the emissions from the power sector and the total electric energy produced by the power sector. Values are based on the Med2C and the WB2C scenarios of the ADVANCE database for respectively the *median2C* and the *below2C* alternatives. In these scenarios, the carbon content can be negative because the emissions reported for the electricity sector are those related to fossil combustion as well as the negative emissions related to the use of bio-energy with carbon capture and storage (BECCS). Other indirect emissions exist throughout the life cycle for each electricity generation technology (Pehl *et al.*, 2017). However, considering them would goes beyond the scope of the paper and would induce double counting of emissions because they include emissions used to produce steel or cement in the electricity generation capital. I assumed for all countries a linear evolution of carbon content of electricity from 2015 to 2050. For countries with carbon contents in 2015 lower than the projected regional values in 2050, the carbon content is assumed to be constant.

3 Results and discussion

Some results are presented in this section following the format *median value (lower value-upper value)* based on the different target values of in-use stock per capita tested to integrate uncertainties (see section 2.2 for description).

3.1 Cement and steel requirement to reach high infrastructure access

I estimated the steel and cement in-use stocks levels in line with providing globally high access rates for each infrastructure service. To do so, I used for each country as targets of stocks per capita either the value derived from global trends or the national stock per capita for the year 2014 (see methodology section for the different cases and underlying assumptions).

This translates into different material requirements depending on the infrastructure considered. On one hand, the global in-use material stock-both cement and steel aggregated-increases by a median value close to 10% on the period 2015-2030 to reach high access levels to water or electricity. Cumulative material demands equal to 7.9 (5.7-10.5) Gt of cement and 1.49 (1.1-1.9) Gt of steel for water and 9.5 (5.7-18.4) Gt of cement and 0.7 (0.6-1.9) Gt of steel for electricity. On the other hand, for transportation access, the aggregated in-use stock increase by a median value of 50% with material demands reaching 49.9 (28.2-73.3) Gt of cement and 6.3 (2.8-16.9) Gt of steel. Sanitation and shelter infrastructures give intermediary results with global in-use material stock increasing by a median value of 26%. In the modelling framework, global population increases by 15% from 2014 to 2030 which highlight the high contribution of access provision for sanitation, shelter and transport infrastructures.

Some results below are presented at regional aggregations of the world to be consistent with the scenarios used for emissions comparison in the next section. The different world regions are Asia, Middle East & Africa (MAF), Latin America and the Caribbean (LAM), Countries from the Reforming Economies of the Former Soviet Union (REF) and the OECD 1990 countries as well as EU members and candidates (OECD90). Composition of the regions can be found in the description of the Advance Scenarios Database (`https://db1.ene.iiasa.ac.at/ADVANCEDB/dsd?Action=htmlpage&page=about`).

Most of the material demand is concentrated in the developing regions ASIA and MAF which represent more than 90% of global demand regardless of the infrastructure considered (figure 3). Within these regions, material demand is unevenly distributed across countries (figure 4). Some countries contributes particularly to the global demand such as India, Nigeria, Indonesia, Pakistan, Bangladesh, Ethiopia, Congo Dem.Rep, the Philippines and Tanzania where material needs are greater than 1 Gt to reach high access levels to transportation infrastructures. One factor is the high population growth over the period 2015-2030, ranging from 21 million inhabitants for Tanzania to 235 million inhabitants for India. Achieving high levels of access in 2030 appears as a challenge in MAF if looking at the relative growth of the in-use material stocks. Water and electricity access, which are the less material intensive objectives, induce a stock multiplication by a factor greater than 15 in Madagascar, Ethiopia, Niger, Tchad, Central

African Republic, Congo Dem. Rep. and Guinea (figure 4).

I compare the cumulative material consumptions I estimated with existing scenarios of global steel and cement production on the same period (van Ruijven *et al.*, 2016; Edelenbosch *et al.*, 2017; Winning *et al.*, 2017; IEA, 2018). I filtered out only baseline scenarios - continuation of past trends regarding the implementation of climate policies or energy/material efficiencies - to be consistent with my estimations. I obtained cumulative values of material either directly from the text or by graphical reading using the software Web Plot Digitizer available at `https://apps.automeris.io/wpd/`. In these scenarios, demand for materials is related to economic activity and population without consideration of infrastructure needs.

The material demand for providing high access to water, electricity and shelter is consistent with these scenarios. The associated global cement and steel demands represent in the median cases respectively at most 35-40% and 10-15% of literature values. If I consider the case of reaching a quasi universal access with a 95% access rate, material needs are as expected higher but still consistent with the existing scenarios in the median cases (figure 3). The consistency of our results with global material production scenarios is less clear, to a smaller extent for sanitation and to a larger extent for transport. It is all the less obvious as I did not consider the cement and steel needed to maintain the capital already installed in 2014, which would lead to additional material needs, particularly in developed countries. For sanitation, it depends on the assumption about the target value of the in-service cement stock per capita. Considering the upper bound leads to a cumulative demand representing 73-84% of literature values. For transportation, median material needs reach the shares of 70-80% for cement and 22-32% for steel compared to values of scenarios from literature. The upper values estimated are even at a similar level for steel and above for cement. In the case of an access rate targeted of 95%, median cumulative demands for both materials are more than doubled increasing to levels higher than any existing values from literature. It calls into question the realism of achieving a high access level to transportation at the global scale in 2030.

3.2 Embodied CO2 emissions

I quantified the CO_2 emissions from the production of materials needed to reach high access level to the different infrastructures in 2030 and also to keep this access level high until 2050 in case of population increase. To do so, I applied three scenarios of emissions mitigations ambition in the cement and steel industries, described in the methodology section : *baseline*, *median2C* and *below2C* scenarios.

For baseline scenarios, I obtain cumulative emissions - including indirect emissions from primary energy conversion into electricity used during the manufacturing process - on the period 2015-2030 from 7.3 (4.6-15) Gt CO_2 for electricity to 42.3 (22.6-80.5) Gt CO_2 for transportation. Assuming that the access rate is kept at a high level until 2050, cumulative emissions for the 2015-2050 period range from 10.3 (6.9-20) Gt CO_2 for electricity to 53 (29.5-99.1) Gt CO_2 for transportation. The major part of emissions come from cement production which represents in baseline scenarios between 67% and 85% of global cumulative emissions depending on the infrastructure considered. For *median2C* and *below2C* scenarios, the values obtained for transportation - the most material-intensive access objective-decrease to respectively 45.6 (25.1-82.9) and 39.5 (21.7-72.2) Gt CO_2.

These results are low compared to most of literature on emissions induced by global infrastructure development (Table 7) for different reasons. Contrary to Lamb & Rao (2015) and Krausmann *et al.* (2020), I only focus on emissions from the steel and cement sectors. Also, projections of steel and cement consumption are not driven by GDP (van Ruijven *et al.*, 2016; Krausmann *et al.*, 2020) or by a convergence of stocks towards richest countries levels (Müller *et al.*, 2013; Krausmann *et al.*, 2020) but by a convergence of stock to *sufficient* levels to assure high infrastructure access. Conversely, our results for transport are much higher than those of Wenz *et al.* (2020) where authors assessed the material requirements and associated emissions specific to road infrastructure to provide basic transportation access. In contrast to this bottom-up and purely normative approach, my methodology here is more descriptive and analyses, in the light of past trends, how the stocks of cement/steel in infrastructure could increase across the whole economy by extending road access to all. The difference between the results is all the more important as, I highlighted before, in most countries high access level for transportation tends to be achieved after having already reached a high level of access to water, electricity, sanitation and shelter.

The cumulative emissions I obtained are compared to the carbon budgets available related to Paris Agreement targets. Carbon budgets available to achieve the 2°C or the 1.5 °C targets (66% chance) are respectively 1170 and 420 Gt CO_2 from 2018 (Rogelj *et al.*, 2018). Adding the 106 Gt CO2 that have been emitted from 2015 to 2017 (Project, 2019), I obtained $C0_2$ budgets of 1276 and 526 Gt CO_2 from 2015. Considering the most pessimistic case- reaching a 90% transport access level in 2030 in baseline scenarios and assuming the upper target of in-use material stock per capita - would consume from 2015 to 2050 about 8% and 19% of the budgets available from 2015 to respectively achieve the 2°C and the 1.5°C targets.

I also analyse the consistency at finer geographical and sectoral scale between the emissions I quantified and the existing CO_2 emissions pathways (figure 5). I use as reference low-carbon scenarios from the ADVANCE database (Luderer *et al.*, 2018; Vrontisi *et al.*, 2018). In this database, nine integrated assessments models have produced a set of global climate policy pathways consistent with limiting temperature increase in the 1.5-2°C range with different levels of short-term ambition. This database has also the advantage of giving quantification of CO_2 emissions in the industrial sector - both process and direct emissions from energy consumption - at the global scale and at a 5 world regions disaggregation (see section 3.1 for regions description).

To be able to compare my results with the ADVANCE scenarios database, I first excluded in this part the indirect emissions - emissions induced by the conversion of primary energy into electricity used- which are aggregated to the electricity sector emissions in the ADVANCE database. Secondly, in order to have an order of magnitude of cement and steel sectors emissions in the database scenarios, I assumed that their share in the total industry sector emissions were similar over time and between the five world regions. The cumulative emissions of the industry sector extracted from the ADVANCE database scenarios were therefore multiplied by 0.55 following IEA (2017b). Finally, to be consistent with the decarbonisation scenarios I applied for the cement and steel sectors in the modelling framework, I selected in the ADVANCE database (i) the *2020 Med2C* and *2030 Med2C* scenarios as comparison references for the *median2C* estimations and (ii) the *2020 WB2C* and *2030 WB2C* scenarios as comparison references for the *below2C* estimations. In the *2020 Med2C* scenarios, mitigation efforts are strengthened after 2020 to limit cumulative 2011-2100 CO2 emissions to 1600 GtCO2, leading to more than 50% to stay below 2°C. In the *2020 WB2C* scenarios, mitigation efforts are strengthened after 2020 to limit cumulative 2011-2100 CO2 emissions to 1000 GtCO2, leading to more than 67% chance of staying below 2°C. In the *2030 Med2C*, after implementing the NDCs without strengthening until 2030, mitigation efforts are strengthened to obtain the same cumulative emissions as in the *2020 Med2C*. In the *2030 WB2C* scenarios, after implementing the NDCs without strengthening until 2030, mitigation efforts are strengthened to obtain the same cumulative emissions as in the *2020 WB2C*.

According to figure 5, providing globally a high level of access to the five infrastructures considered in this study leads to emissions related to cement and steel requirements lower than the cumulative emissions of these sectors from the ADVANCE low-carbon scenarios on the same period. This result is also valid for the world regions ASIA, LAM, OECD and REF where the cumulative emissions resulting from this modelling represent a maximum of 67% of cumulative emissions from the corresponding reference scenarios (figure 5). However, for the MAF region, providing a high level of access to sanitation and transportation induces emission levels that are of the same magnitude order than some estimations of the ADVANCE corresponding scenarios. For transportation, our median estimates are even above the lower bounds of the ADVANCE scenarios estimations regardless of the climate ambition level.

4 Conclusion

Manufacturing the cement and steel materials required for infrastructures is an important source of greenhouse gas emissions. In this paper, I assess if high level of access to 5 basic infrastructure services - electricity, water, shelter, sanitation and transportation - can be provided at the global scale in 2030 and until 2050 without compromising climate mitigation targets. Following historical patterns, I first quantify the cement and steel requirements in each country associated with providing high access levels. I then estimate the production-based carbon dioxide emissions related to manufacturing the cement and steel needs. To do so, I model influencing factors such as national production technologies mix, trade structure and mitigation actions in the cement and steel industries.

According to past trends, I highlight that (i) from a certain access threshold a small increase of access rate is associated with a high increase of material stocks and that (ii) infrastructure access tends to follow a sequencing process along material stocks increase with electricity and water coming first, and transportation access last. I show cement and steel demand associated with providing in 2030 global high access level (90%) would be concentrated in Asia and Middle-East & Africa regions. In this latter region, achieving high access level in 2030 appears as challenging if looking at the relative growth of the cement and steel stocks. For water, electricity and shelter access, I find global cement and steel requirements are consistent with existing global projections of cement and steel production. I obtain on the contrary less consistent results to a smaller extent for sanitation and to a larger extent for transportation. This calls into question the realism of achieving high levels of access to these infrastructures in the short term. I find global cumulative embodied emissions from 2015 to 2050 from cement and steel requirements would represent small shares of the carbon budgets associated with the Paris agreement objectives. Assuming relative decoupling of cement and steel production from CO_2 emissions following existing industry roadmaps, I find on the same time period lower cumulative emissions than those of the steel and cement sector from existing low-carbon pathways, at the global scale and for four world regions over five. However this result doesn't stand for sanitation and transportation access in the Middle-east & Africa region.

This work has some limitations related to the chosen methodology. First, I based this study on infrastructure access indicators which, like all indicators, have their limits. For example, for transportation, the indicator only relates to the geographical proximity of the road network and says nothing about the availability of vehicles for the effective use of the network or about the modal split allowing the satisfaction of human welfare for all. Second, I assumed the trade structure evolution constant which could be refined in order to assess the effects of heavy industries relocation or taxes on imported materials, as the United States recently did on Chinese steel. Third, potential influencing factors of technology production choice such as capacity installed, production price or steel scrap availability should be integrated in future research.

This work could also be extended to estimate the materials needed specific to each type of infrastructure service. This could be done with bottom-up modelling analyses using life cycle assessment and industrial ecology data, as it has been done recently to quantify final energy consumption required for decent living (Rao *et al.*, 2019; Millward-Hopkins *et al.*, 2020). Also, a spatialized estimation of infrastructure and construction material needs would be an interesting approach, as recently carried out by Wenz *et al.* (2020) on road access, in order to take into account the geographical disparities of infrastructure access at finer scales.

However, these approaches would necessarily lead to lower values of cumulative material demand and CO_2 emissions, assuming countries would only focus on providing access to the whole population, in a purely normative approach. My methodology here is more descriptive in order to analyse, in the light of past trends, how countries could increase their stocks of cement/steel in infrastructure across the whole economy by extending access to all. It complements a bottom-up approach in four ways. First, it takes into account the chronology of access in development (e.g., access to transport comes after access to electricity and water). Second, infrastructure can be considered as a 'system-of systems' in which different types of infrastructure act in concert to deliver services (Hall *et al.*, 2016) and my methodology allows to integrate this interdependence at the level of the economy (e.g., a certain level of transport infrastructure is needed to provide access to water). Finally, it takes into account the influence of current socio-political configurations which can induce an infrastructure stock growth that is not necessarily 'basic-needs oriented' but support increasing use among those with access.

I can provide a twofold interpretation based on this study. A first interpretation is that the 'carbon space' left in the existing global low-carbon scenarios is too limited to allow the basic infrastructures development in emerging countries in the short to medium term. This interpretation is close to Steckel *et al.* (2013) where authors highlighted that mitigation scenarios could be too optimistic with respect to energy consumption in developing countries. While this ensures global efficiency, cost-optimal approaches used in these scenarios do not lead to equitable results as it disproportionately burdens less affluent countries (Leimbach & Giannousakis, 2019;

van den Berg *et al.*, 2019).

A second interpretation is that relying solely on the decarbonisation of the steel and cement sectors is not enough to achieve the goals of access to basic infrastructure services by 2030 without compromising the climate mitigation targets. Other levers must therefore be used in the short term. Material efficiency is a first significant opportunity decreasing the cement and steel consumption for the same infrastructure services. It could take different forms as a more intensive use of existing capital (lifetime extension, reducing per capita floor area...) or the reuse of steel and cement components (Hertwich *et al.*, 2019; Pongiglione & Calderini, 2014). Substitution to less intensive construction materials is another potential lever such as using timber over steel and concrete in buildings construction (Churkina *et al.*, 2020; Heeren *et al.*, 2015). More research is needed to understand the underlying drivers of cement and steel accumulation along the development process to implement relevant policy instruments for lower usage of cement and steel.

Climate policies can therefore make it possible to reconcile the satisfaction of essential needs for infrastructure services and the reduction of CO_2 emissions but only by ensuring a triad of conditions: a fast decarbonisation of the steel and cement sectors, a reduction in the need for steel and cement, and a strengthening of emission reduction efforts in developed countries. The national determined contributions are currently inconsistent with the Paris Agreement objective of limiting global average temperature increase to well below 2°C (Höhne *et al.*, 2020) and should be enhanced during the 2023 global stocktake. This 'ratcheting-up' process will most likely include some evaluation of fairness where the question of carbon emissions spaces to allow 'sufficient' development in developing countries should be be discussed. Also, the crucial role of cement and steel sectors for sustainable development suggests that these sectors should be taken out of national policy discussions and put at the heart of international climate negotiations in order to foster cooperation between countries for inducing technological leapfrogging.

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Services	**SDG target**	**Official indicator**	**Chosen indicator**	**Coverage**	**Source**
Electricity	7.1 Universal access to affordable, reliable and modern energy services	Percentage of population with access to household electricity	Percentage of population with access to household electricity	214 countries, 1990-2014	World Bank (2018)
Water	6.1 Universal and equitable access to safe and affordable drinking water for all	Proportion of population using safely managed drinking water services	Percentage of population having access to an improved water source	203 countries; 1990-2015	World Bank (2018)
Sanitation	6.2 Access to adequate and equitable sanitation and hygiene for all and end open defecation	Proportion of population using safely managed sanitation services	Percentage of population having access to improved sanitation facilities	202 countries, 1990-2015	World Bank (2018)
Shelter	11.1 Adequate, safe and affordable housing and basic services and upgrade slums	Proportion of urban population living in slum household	Proportion of urban population not living in slum household	96 countries; 2000, 2005, 2007, 2009 and 2014	World Bank (2018)
Transport	9.1 Develop quality, reliable, sustainable and resilient infrastructure, including regional and trans-border infrastructure	Proportion of the rural population living within 2 km of an all-season road	Proportion of population living within 2 km of an all-season road	151 countries, 2014	Mikou *et al.* (2019)

Table 1: Description of infrastructure access data

In-use material stock	**Coverage**	**Source**
Cement	184 countries. 1990-2014. All sectors aggregated	Cao *et al.* (2017)
Steel	139 countries. 1990-2008. Sector "buildings-construction-infrastructure"	Pauliuk *et al.* (2013)

Table 2: Description of in-use material stock data. I assumed in-use steel stock equal to in-use iron stock following Morfeldt *et al.* (2015).

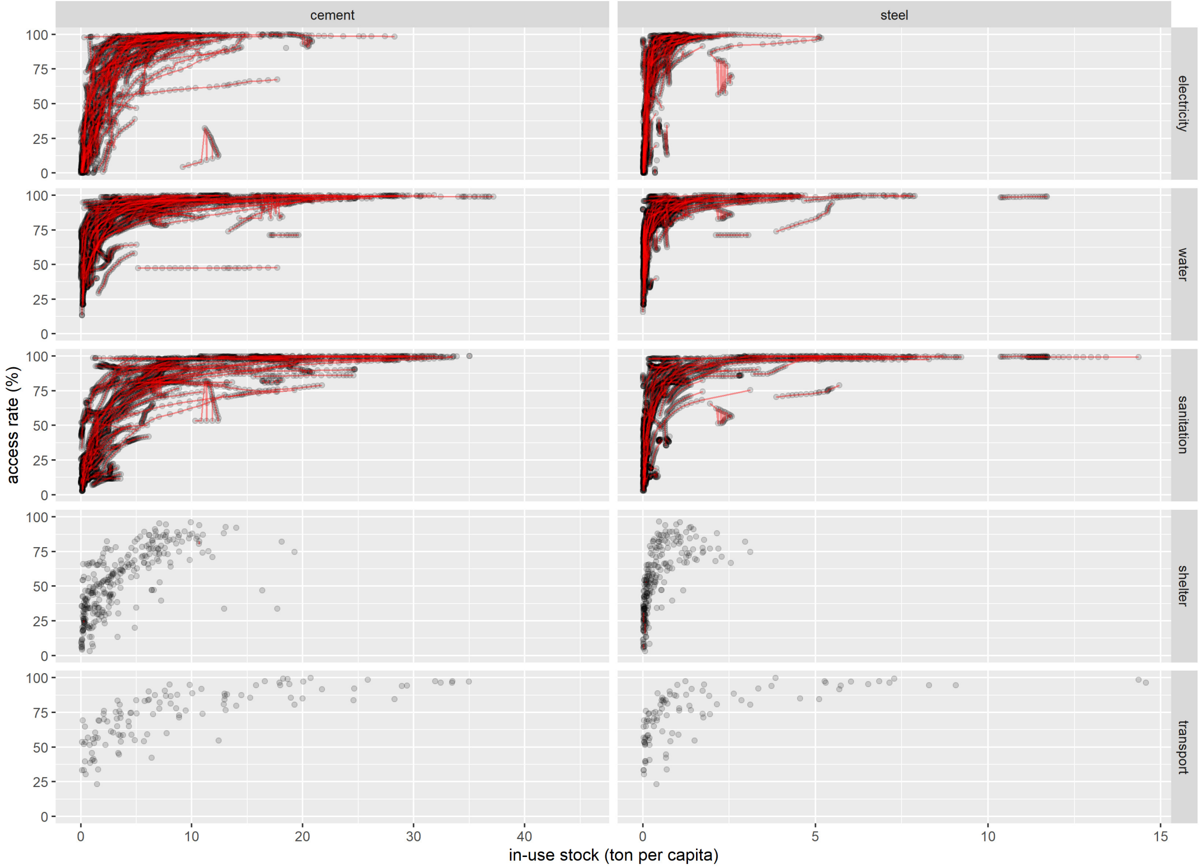

Figure 1: Scatter plots of infrastructure access rates against in-use material stocks. The samples have been filtered out by removing values of 0% and 100% access rates for readability purpose. Steel stock has been projected from 2008 to 2014, assuming the ratio of the cement stock growth rate to the steel stock growth rate was the same as the 2005-2008 period for each country. Each line refers to the evolution for a country. Lines are not drawn for shelter and transport scatter plots since access data is not available for consecutive years.

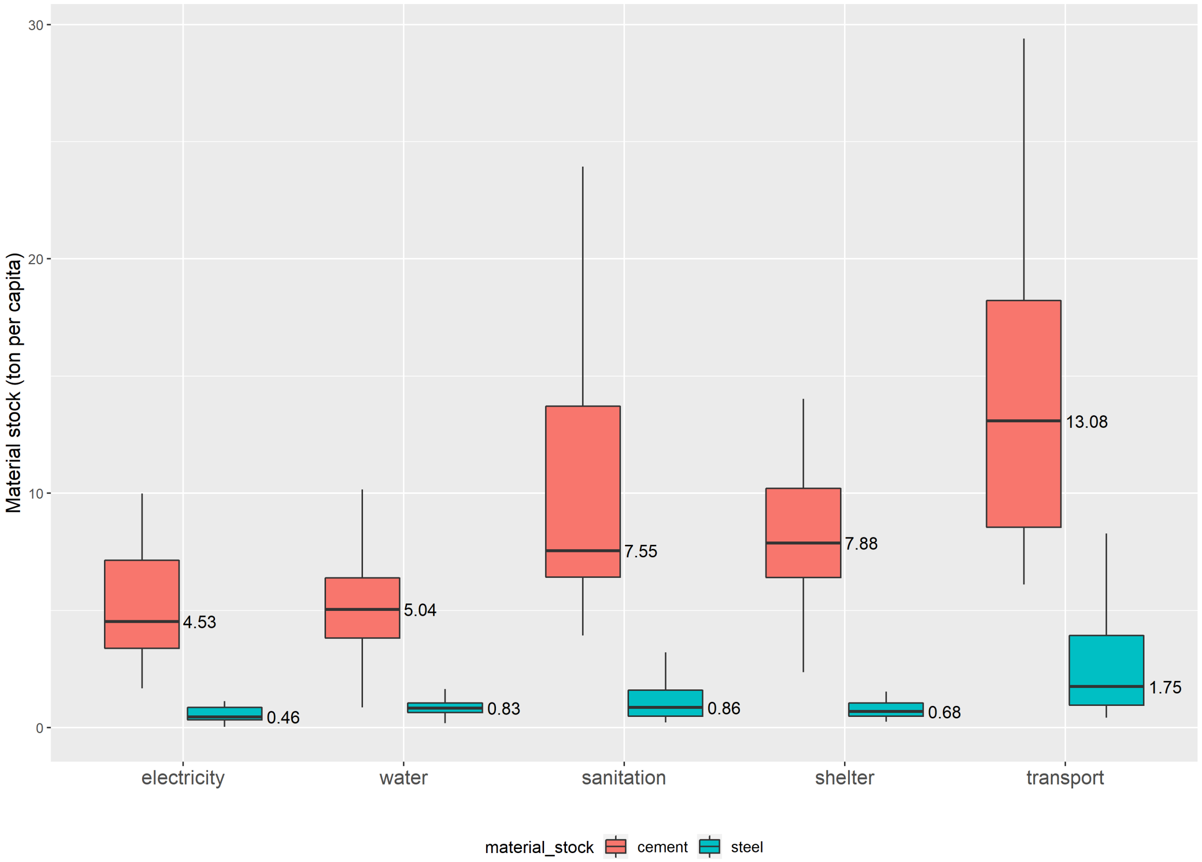

Figure 2: Distribution of in-use cement and steel stocks per capita for the 20 countries with the access rate closest to 90%. These values represent the materials embodied in the whole infrastructure stock and should not be considered as materials used specifically for a infrastructure type.

Access rate in 2014	**In-use stock per capita in 2014**	**In-use stock per capita targeted**	**Underlying assumptions**
<90%	<Global median value associated with a 90% access rate	Global median value associated with a 90% access rate	Countries are still in the development process so the in-use stocks per capita will increase.
<90%	>Global median value associated with a 90% access rate	2014 value	Countries with access rates below 90% are still in the development process so the in-use stocks per capita will not decrease
>90 %	<Global median value associated with a 90% access rate	2014 value	Country specific conditions allows lower in-use stocks levels per capita than global median value to provide high infrastructure access. In-use stocks levels per capita will saturate in developed countries.
>90%	>Global median value associated with a 90% access rate	Global median value associated with a 90% access rate	Country specific conditions lead to higher in-use stocks levels per capita than global median value to provide high infrastructure access. In-use stocks levels per capita can decrease in the highly developed countries

Table 3: Description of the different conditional cases to allocate targets of in-use material stock per capita to each country. The way in which the different cases are constructed gives rather lower bound to target. I also applied the same methodology replacing the global median values by the first and third quartiles.

Process routes	**Direct emissions (CO_2/ton steel)**	**Electricity consumption (kWh/ton steel**
BF-BOF	2.19	226
Scrap-EAF	0.17	625
DRI gas-EAF	1.55	754
DRI coal-EAF	2.95	759
OHF	2.91	300

Table 4: Carbon and electricity intensities of the different steel production routes. Values have been calculated using data from Morfeldt *et al.* (2015) and Milford *et al.* (2013)

Sector	**Quantity**	**Source**	**Comments**
Electricity	Grid carbon intensity	IEA (2017a)	142 countries for the year 2015
Steel	Production route shares (%)	World Steel Association (2016)	89 countries for the year 2015
	Carbon intensity of the production routes (t CO2/t steel)	Morfeldt *et al.* (2015); Milford *et al.* (2013)	see Table 3 for calculated values
	Electricity intensity of the production routes (kWh/t steel)	Morfeldt *et al.* (2015); Milford *et al.* (2013)	
	Bilateral traded flows (t steel)	BACI database (Gaulier & Zignago, 2010)- HS codes from 7206 to 7306	207 countries for the year 2015
	Domestic production (t steel)	World Steel Association (2016)	91 countries for the year 2015
Cement	Clinker/cement ratio (%)	WBCSD (2016) - variable 92AGW	11 world regions for the year 2015
	Carbon intensity of the fuel mix (g CO2/MJ)	WBCSD (2016) - variable 593AG	
	Thermal energy consumption (MJ/t clinker)	WBCSD (2016) - variable 93AG	
	Electricity intensity of cement production (MWh/t cement)	WBCSD (2016) - variable 33AGW	
	Clinker CO2 emissions factor (t CO2/t clinker)	Eggleston *et al.* (2006)	

Table 5: Description of the data used to represent the steel and cement sectors.

	baseline	**median2C**	**below2C**
Grid emissions	Constant	2050 : From -35 to 54 g$CO2$/kWh Differing on world regions	2050 : From -89 to -10 g$CO2$/kWh Differing on world regions
Trade structure	Constant	Constant	Constant
Direct cement emissions	Constant	2030 : 0.52 t CO_2/t cement 2050 : 0.37 t CO_2/t cement	2030 : 0.41 t CO_2/t cement 2050 : 0.2 t CO_2/t cement
Direct steel emissions	Constant	2030 : 1 t CO_2/t cement 2050 : 0.7 t CO_2/t cement	2030 : 0.7 t CO_2/t cement 2050 : 0.33 t CO_2/t cement

Table 6: Evolution of parameters in the different scenarios of cement and steel sectors decarbonisation

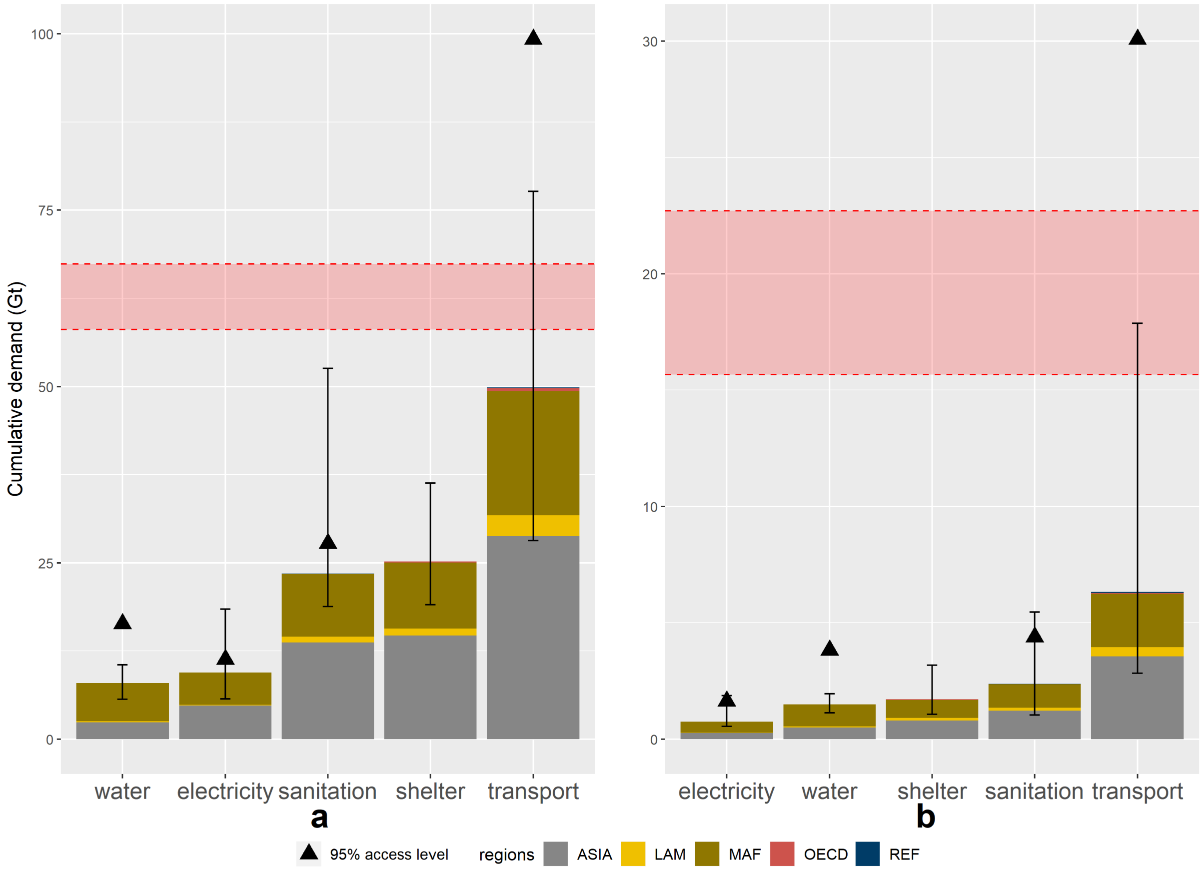

Figure 3: Global cumulative material demand of cement (a) and steel (b) from 2015 to 2030 associated with meeting high access rate (90%) to different infrastructures. Material consumption levels are presented here in a sequential manner to be consistent with high access levels to the different infrastructure services. Red area represents the range of values from existing cement and steel production scenarios (van Ruijven *et al.*, 2016; Edelenbosch *et al.*, 2017; Winning *et al.*, 2017; IEA, 2018). They are considered as 'baseline' trajectories meaning a continuation of past trends regarding the implementation of climate policies and energy material efficiencies. Error bars are constructed by deriving from past trends low or high target values of in use material stock per capita. Triangles represent the cumulative demand (median value) for a 95% access rate except for shelter where data is not available.

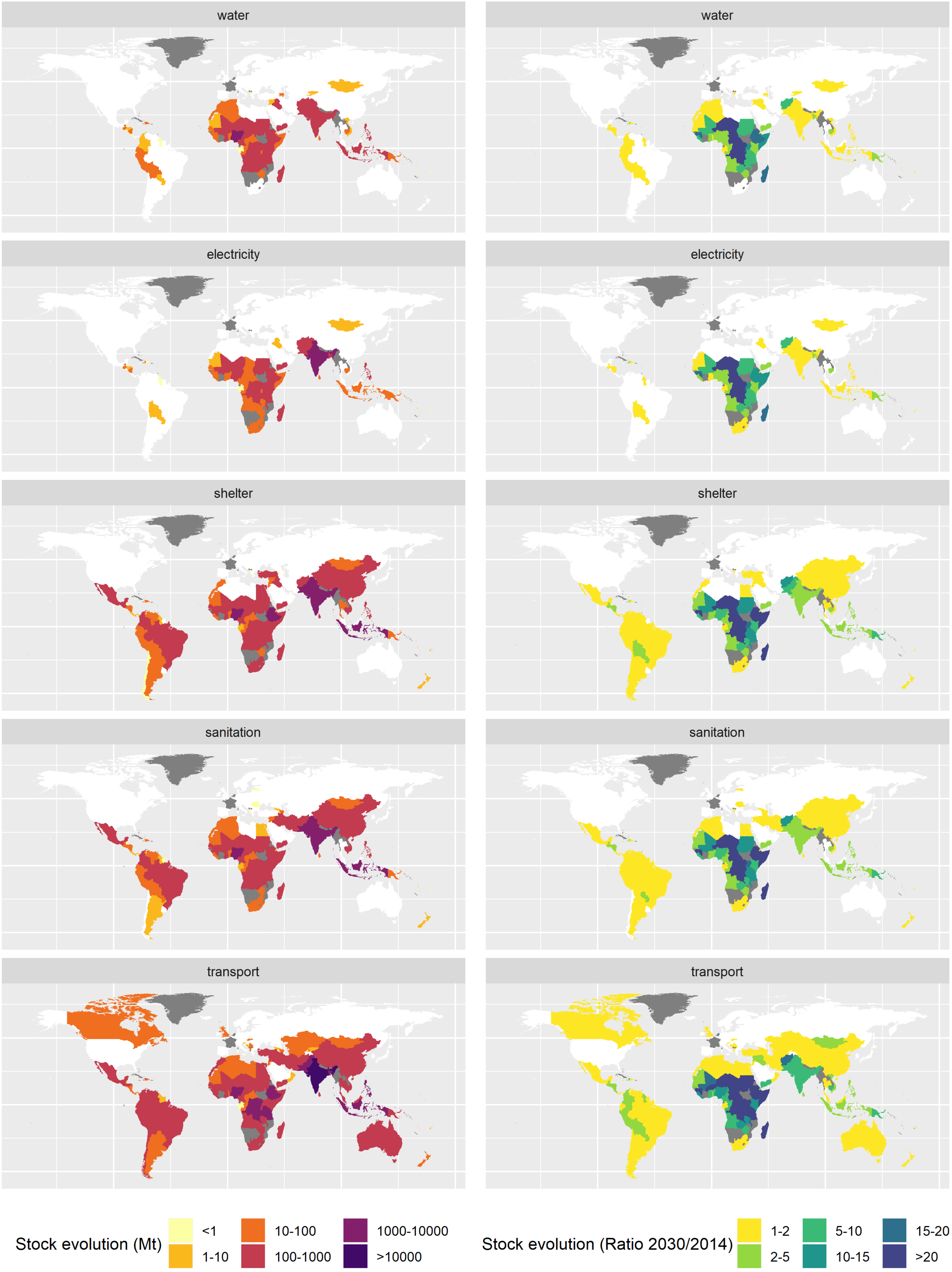

Figure 4: Net addition to material stock - cement and steel together - at national scale from 2015 to 2030 associated with reaching high infrastructures access

Study	**Infrastructure**	**Emissions (Gt CO2)**	**Modelling framework**
This study	Electricity	9.7 (6.5-18.7)	2015-2050; Convergence to overall infrastructure system wide-in-use stock levels per capita that are consistent with high infrastructure access rates; CO_2 emissions from steel and cement sectors
	Water	10.3 (6.9-20)	
	Sanitation	24.8 (18.3-53.9)	
	Shelter	24.7 (18.7-36.3)	
	Transportation	53 (29.5-99.1)	
Wenz *et al.* (2020)	Transportation	0.5	From 2015 (static analysis) ; Geographically explicit estimation of construction requirements to provide high road access level; CO_2 emissions from the production of materials used for road construction
Krausmann *et al.* (2020)	Unspecified	500-880	2018-2050 ; GDP driven material consumption or convergence to in-use stock levels per capita of wealthiest countries ; CO_2 emissions from system-wide stock-manufacturing (maintenance and expansion)
van Ruijven *et al.* (2016)	Unspecified	245	2015-2050; GDP driven material consumption ; CO_2 emissions from cement and steel sectors
Lamb & Rao (2015)	Composite access indicator including sanitation, water and electricity	1003	2015 -2050 ; Energy consumption related to the access indicator value; GHG emissions from all sectors
Müller *et al.* (2013)	Unspecified	350	2008-2050 ; Convergence to system-wide in-use stock levels per capita of wealthiest countries ; CO_2 emissions from cement, steel and aluminium sectors

Table 7: Comparison of global cumulative emissions with the literature. All these results have been obtained using scenarios without mitigation policies, assuming no further decarbonization in the future or consistent with past trends.

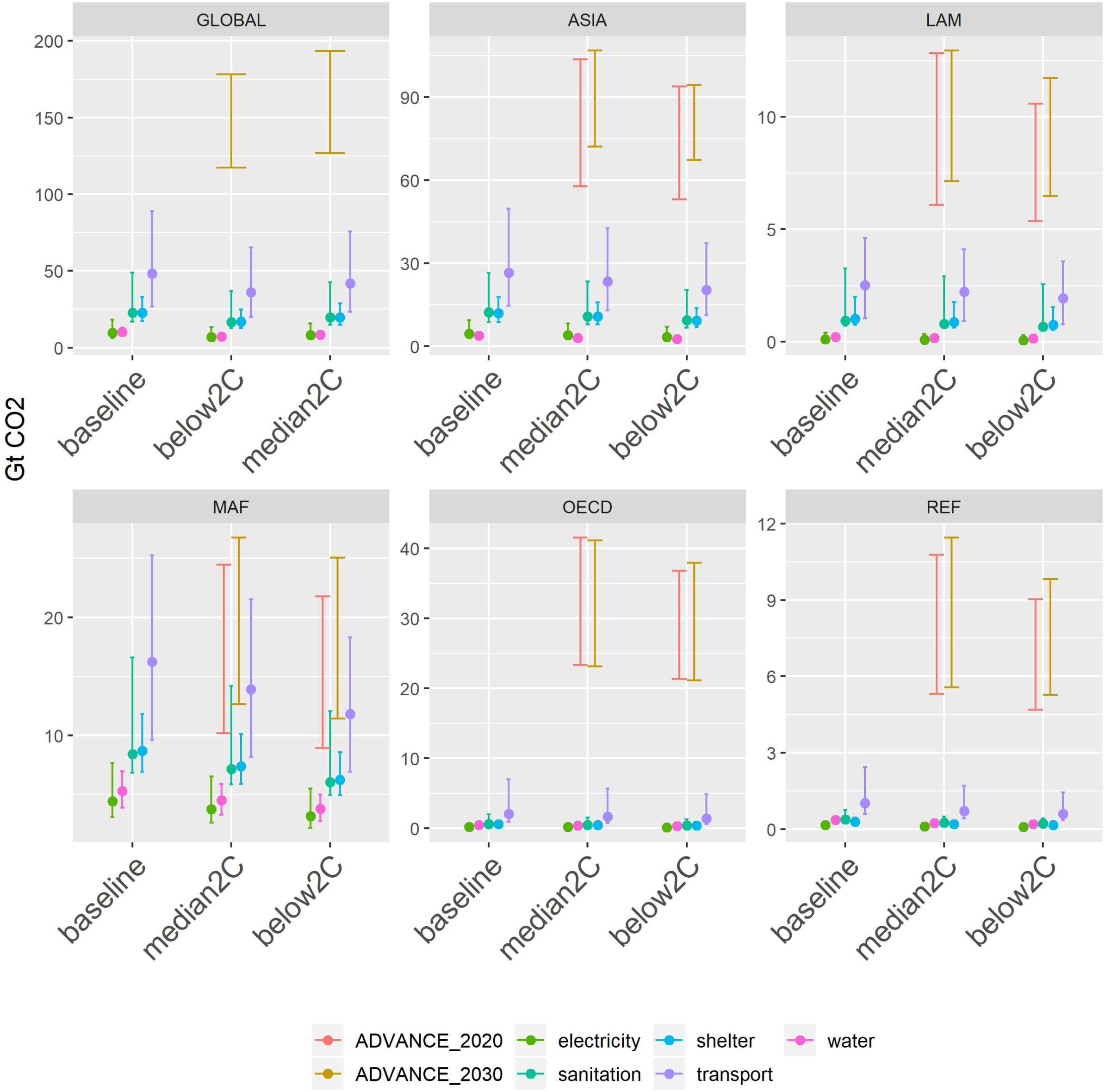

Figure 5: Cumulative emissions (direct and process-related) from 2015 to 2050 associated with the cement and steel requirements to reach a 90% access level. Points represent the central value of the estimations for each combination of infrastructure and mitigation ambition in the cement and steel sector. Vertical line represent the range of cumulative emissions between the lower and upper target values of in-use stocks per capita. Bars show the range of estimations from the ADVANCE scenarios database.