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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

## HAL Id: hal-03353919 https://hal.science/hal-03353919

Submitted on 16 Oct 2023

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# 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

1

Access to infrastructure services is essential to meet human basic needs. However, 2 infrastructure construction requires carbon-intensive materials, first and foremost cement 3 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 5 scale in 2030 and until 2050 without compromising climate mitigation targets. Follow-6 ing historical patterns, I first quantify the cement and steel requirements in each country 7 associated with providing high access levels. I then estimate the production-based car-8 bon dioxide emissions related to manufacturing the cement and steel needs. To do so, I 9 model influencing factors such as national production technologies mix, trade structure 10 and mitigation actions in the cement and steel industries. Global cumulative material 11 demand (central values) to reach high access level in 2030 is the lowest for water with 8 12 Gt of cement and 1 Gt of steel and the highest for transportation with 50 Gt of cement 13 and 6 Gt of steel. Most of the cement and steel demand is concentrated in Asia, Middle-14 East and Africa. I show for all infrastructure services that achieving high access level in 15 2030 and until 2050 induces cumulative carbon dioxide emissions well below the carbon 16 budgets related to Paris Agreement targets, with central values under baseline scenario 17 from 10 to 53 Gt  $CO_2$  depending on the infrastructure service. However, I find providing 18 high sanitation and transportation access in Middle-East and Africa conflicts with exist-19 ing low-carbon pathways. This calls for on one side implementing material efficiency and 20 substitution towards less carbon-intensive construction materials, and on the other side 21

- strengthening mitigation efforts in wealthiest countries to leave enough 'carbon space' for
- 23 basic infrastructure development in emerging countries.
- 24 Keywords— basic needs; infrastructure access; embodied carbon dioxide emissions

## <sup>25</sup> 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 39 between the dimensions and requires to assign weights to them (Decance & Lugo, 2013). Doval 40 & Gough (1991) and Max-Neef et al. (1992) have proposed a set of universal human needs 41 to fulfill. In the human needs theories, needs are plural, non-substitutable, satiable, cross-42 generational and universal but the way to satisfy them (need satisfiers) can differ between 43 regions such as the type of food or dwelling. Doyal & Gough (1991) distinguished two basic 44 needs-personal autonomy and health- that depend on other intermediate needs such as security 45 in childhood or clean water. Gough (2015) updated this analytical framework and highlighted 46 the need to define 'sufficient' levels for human needs regarding the environmental constraint. 47

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 54 of many development goals either directly or indirectly (Thacker et al., 2019). This pivotal role 55 is evident for the SDG 9-Build resilient infrastructure, promote inclusive and sustainable indus-56 trialization and foster innovation. Infrastructure stock is one of the factors explaining economic 57 growth (Calderón & Servén, 2004; Straub, 2011) and hence contributes to the achievement of 58 the SGD 8 - Promote inclusive and sustainable economic growth, employment and decent work 59 for all. It is also a determinant of poverty reduction (Akanbi, 2015; Ogun, 2010) which is 60 essential for the SGD1-End poverty in all it forms everywhere. Infrastructure is an instrument 61 to provide essential services to meet human needs (Steckel et al., 2017; Clark et al., 2018) such 62 as water, sanitation or transport. However, access to basic infrastructures varies widely among 63 countries even when incomes are similar (Steckel et al., 2017). 64

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.

<sup>71</sup> Most of the embodied emissions come from cement and steel productions, which are  $CO_2$ <sup>72</sup> intensive industries. These two core materials are used in all countries at any development <sup>73</sup> stage for construction, the other construction materials such as aluminium and cooper being <sup>74</sup> specific to more advanced applications (Bleischwitz *et al.*, 2018). In 2014, the steel and cement <sup>75</sup> 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 89 access levels to different infrastructure services but without considering the embodied  $CO_2$ 90 emissions in construction materials. Some studies have estimated the  $CO_2$  emissions from final 91 energy use to expand energy access and have found a small contribution to global warming 92 (Chakravarty & Tavoni, 2013; Pachauri et al., 2013, 2014). Other studies have analysed empir-93 ically the relationship between GHG emissions or energy consumption - all sectors aggregated -94 and access levels to basic infrastructure such as water, sanitation or electricity (Rao et al., 2014; 95 Lamb & Rao, 2015; O'Neill et al., 2018). They have highlighted the best fit curves are either 96 linear-logarithmic or saturation curves. This suggests that after a certain threshold of access, 97 a low increase of access level is associated with a high carbon impact. Lamb & Rao (2015) 98 and O'Neill et al. (2018) have also projected the system-wide carbon emissions associated with 99 the achievement of high access rates to sanitation, electricity or water but only in pathways 100 unconstrained by mitigation actions. 101

Another literature strand has projected the energy consumption and  $CO_2$  emissions from 102 cement and steel sectors but without considering whether or not infrastructure access needs 103 were provided. Several studies have used econometric relationship between cement or steel 104 production and GDP (Zhang et al., 2018; van Ruijven et al., 2016; Steckel et al., 2013). Among 105 them, Steckel et al. (2013) suggested a potential tension between energy consumption decrease 106 in existing scenarios and the energy necessary for infrastructure build-up. Other studies from 107 industrial ecology field have used the concept of in-use material stock to link the increase of 108 infrastructure and the material flows required (and the associated embodied emissions) to build 109 it up (Pauliuk et al., 2017; Chen & Haynes, 2015). Müller et al. (2013) showed an extension 110 at the global scale of wealthiest countries' in-use stock levels for cement, steel and aluminium 111

would consume a significant part of the carbon budget available to stay below 2°C. Although, 112 the convergence of developing countries to infrastructure level of wealthiest countries would 113 be associated with higher access level to basic infrastructures, this objective is questionable 114 because of potential negative outcomes such as land take (Colsaet *et al.*, 2018) and it could not 115 induce significant progress for countries with already high access rates (O'Neill et al., 2018; Rao 116 et al., 2014). Krausmann et al. (2020) has recently estimated the embodied  $CO_2$  emissions - all 117 materials considered - for a global convergence at the per-capita level of in-use stocks that the 118 developed countries had achieved in 1970, considering it as 'sufficient' in terms of life quality. 119 Authors highlighted large reductions in global resource demand and emissions compared to the 120 scenario where countries converge to the current infrastructure level of industrialized countries. 121 Few studies have focused on the carbon/energy embodied in construction materials to pro-122 vide access to basic infrastructure. Two studies have bottom-up estimated using life cycle 123 analysis and input-output tools the energy needs - including the energy used in building some 124 basic infrastructure - to provide decent material living standards to the full population in three 125 countries (Rao et al., 2019) and at the global scale (Millward-Hopkins et al., 2020). Wenz et al. 126 (2020) quantified the cumulative embodied  $CO_2$  emissions associated with building global road 127 network to provide universal access to road. 128

In this paper, I first use historical data to describe the global trends of access to 5 basic 129 infrastructure services - electricity, water, sanitation, shelter or transport - in relation to the 130 steel and cement embodied in infrastructure stocks. Then, following historical patterns, I 131 quantify the amounts of cement and steel needed in each country associated with reaching 132 high access levels in 2030 and kept access levels high until 2050 for each of the infrastructure 133 services. Finally, I estimate the cumulative  $C0_2$  emissions from manufacturing cement and 134 steel requirements. I discuss my findings with respect to the available carbon budgets and the 135 existing scenarios of material production and greenhouse gas emissions in the cement and steel 136 industries. 137

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.

## $_{148}$ 2 Methodology

In a first step, I used historical data to quantify the cement and steel consumption for each 149 country to provide high access levels to different infrastructure services in 2030 and until 2050 in 150 case of population changes. Subsection 2.1 describes the data and the global historical patterns 151 of infrastructure access along the material stocks increase. Subsection 2.2 details the modelling 152 approach used in this step. In a second step, I quantified the  $CO_2$  emissions corresponding 153 to the material consumptions obtained in the previous step. Subsection 2.3 describes how I 154 represented in the modelling framework country-specific determinants of  $CO_2$  emissions related 155 to cement and steel consumption. 156

## <sup>157</sup> 2.1 Analysing trends in infrastructure access levels along the in-use <sup>158</sup> material stocks build-up

### 159 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 167 et al. (2010) for power distribution).

Different indicators of access are available in the literature for each infrastructure service. 168 For instance, for transportation access, researchers have used in the literature the Rural Access 169 Index (Iimi et al., 2016) defined as the proportion of population living within 2 km of an all-170 season road, the travel time required to reach the nearest urban centre (Weiss et al., 2018) or 171 the share of paved roads (Jakob et al., 2016). I privileged the official indicators used to assess 172 sustainable development goals progress or those closest to, depending on data availability (Table 173 1). The complete list of indicators used in the SDGs is available at https://unstats.un.org/ 174 sdgs/indicators/indicators-list/. 175

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 180 domestic cleaning. Inadequate access to safe drinking water is associated with diarrhoea dis-181 ease and exposure to chemical pollutants (Hunter *et al.*, 2010). This is related to the SDG 182 6.1 "Universal and equitable access to safe and affordable drinking water for all". The official 183 indicator is the percentage of people using safely managed drinking water services. I used the 184 percentage of population having access to an improved water source such as piped household 185 water, public tap, tube well/borehole, protected dug wells, protected springs or rainwater col-186 lection. This indicator is close in definition to the official one and has better geographical and 187 temporal coverages. 188

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 <sup>196</sup> indicator is close in definition and has better temporal and geographical coverages.

<sup>197</sup> Shelter access indicator is defined as the proportion of urban population that does not <sup>198</sup> live in slum household. A slum household is considered here as a group of individuals living <sup>199</sup> under the same roof lacking one or more of the following conditions: access to improved water, <sup>200</sup> access to improved sanitation, sufficient living area, and durability of housing. It is the official <sup>201</sup> indicator of the SDG 11.1 "*Ensure access for all to adequate, safe and affordable housing and* <sup>202</sup> *basic services and upgrade slums*".

Transportation accessibility contributes to personal autonomy, and has an impact on em-203 ployment (Johnson et al., 2017) and leisures participation (Kessides, 1993). It can be linked 204 to the SDG 9.1 "Develop quality, reliable, sustainable and resilient infrastructure, including 205 regional and trans-border infrastructure". The official indicator associated is the Rural Access 206 Index (RAI) defined as the proportion of the rural population living within 2 km of an all-season 207 road. Although mobility can also take place by rail, this indicator can be considered as a proxy 208 for transportation accessibility by assuming that railway lines are mostly doubled with roads. 209 I modified this indicator to get the share of the overall population living within 2 km of an all 210 season road using urbanization rate data, assuming all urban inhabitants live within 2 km of 211 an all-season road. 212

I aim to relate the cement and steel materials consumption to the access to infrastructure 213 services. However, linear meters of infrastructure and construction materials used are not 214 available at the country scale and for each infrastructure service. I therefore based the analysis 215 on data of in-use stocks of cement and steel which are the amounts of steel and cement contained 216 in the installed capital stocks (Chen & Haynes, 2015). Researchers have characterized historical 217 patterns of cement and steel stocks tracking the different flows and stock dynamics and taking 218 into account the capital lifetime containing the material. Data and sources for in-use material 219 stocks are synthesized in Table 2. I describe in the next subsection the methodology to break 220 down the stock estimates into the different service categories. Although also contributing to 221 basic needs, I did not consider in this study the steel contained in basic appliances or vehicles. 222 Including these categories goes beyond the scope of this article as they are mobile stock and 223 not infrastructure (Lanau et al., 2019). It would also imply heavy hypothesis at the regional 224

scale on life duration and recycling rate on the time period studied.

### 226 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 234 stock that are consistent with high access level for each infrastructure service. I first defined 235 as high access level a percentage of the population in each country having access to an infras-236 tructure service. I recognize this process is normative. Even though in the SDG framework 237 universal access to infrastructure services is targeted, some indicators are today below 100%238 in the wealthiest countries for transportation or sanitation access. I hence considered the level 239 of 90% as target following Lamb (2016) and Rao *et al.* (2014). I also tested the 95% value for 240 illustrative purpose and to show the sensitivity of the results to a higher coverage level. 241

Following O'Neill et al. (2018), I selected for each infrastructure service the 20 country-year 242 observations where access rates were closest to the access threshold targeted (90% or 95%)243 and then extracted the values of per capita in-use stocks of cement and steel. The 20 values 244 sample allows to get a representative subset of the points closest to the access threshold without 245 deviating too far from it. For each country, I only kept the observation with the access rate 246 closest to the access threshold targeted so that a country's own performance does not unduly 247 influence the overall result. Since transportation access data was available only for the year 248 2014, I projected steel stock values from 2008 to 2014, assuming that the ratio of the cement 249 stock growth rate to the steel stock growth rate was the same as the 2005-2008 period for each 250 country. I then identified the distribution and the median value of material stocks per capita 251 on this subsample and compared them according to the infrastructure or material considered. 252

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 20 257 countries with the access level closest to 90%. The median values differ between infrastructure 258 type and materials to achieve high access rates. Values are higher for cement than steel for all 259 infrastructures considered, with a factor ranging from 6 for water to 12 for shelter. While the 260 lowest values obtained are for electricity with 4.53 tons of cement per capita and 0.46 ton of 261 steel per capita, these values are the highest for transportation reaching respectively 13.08 tons 262 of cement per capita and 1.75 ton of steel per capita. Infrastructure access tends to follow a 263 sequencing process along material stocks increase with electricity and water coming first, and 264 transport access last, which is in line with previous results (Steckel et al., 2017). For the year 265 2014, only 10 countries reach an access rate to sanitation services without having done the 266 same for either electricity or water. 8 countries reach an access rate to transportation higher 267 than 90% without having done the same on one of the other infrastructure. 268

# 269 2.2 Estimating the cement and steel requirements in each country to 270 reach high infrastructure access

The global median values of in-use material stocks per capita associated with high infrastructure 271 access, obtained in the last section, may seem plausible as targets for developing countries. 272 However, some countries have already reached the access level of 90% on some infrastructure 273 for lower values of in-use material stocks per capita. Conversely, other countries have not yet 274 reached the access level of 90% on some infrastructures for higher values of in-use material stocks 275 per capita. Country specific determinants such as the urbanization level or spatial organization 276 affect the cement and steel consumption in each country when economic development levels are 277 similar. Higher urban density decrease the materials stocked in networked infrastructures but 278 increase the structural material stock contained in buildings because of greater height (Norman 279 et al., 2006; Schiller, 2007). Construction techniques and materials used can also differ between 280

<sup>281</sup> countries. Explicitly integrating the influence of these parameters goes beyond the scope of
<sup>282</sup> this study and could be done in further research.

I hence refined the median estimation approach to represent partially country specific pat-283 terns of cement and steel consumption and to represent two stylized facts observed in the 284 literature about cement and steel in-use stocks : (i) cement and steel stocks per capita increase 285 during the development process before saturating or decreasing for wealthiest countries and 286 (ii) material stocks are immobile for many decades and will not decrease in the short term 287 (Cao et al., 2017; Bleischwitz et al., 2018). I considered different conditional cases summarized 288 in the table 3 to allocate to each country and for each infrastructure service a level of in-use 289 materials stocks per capita to reach for providing high access. The way in which the different 290 cases are constructed gives rather lower bound of in-use stocks to target. I also performed the 291 same analysis replacing the global median value by the first and the third quartiles of the dis-292 tributions obtained in the previous methodology step to integrate uncertainties. This approach 293 is also relevant to limit the discontinuities effects induced by the different conditional case for 294 countries with access rates close to 90% or in-use stock per capita close to the global median 295 value. 296

I then estimated the cement and steel needs to reach in 2030 the in-use stocks per capita 297 targeted in 2030 and to keep it at this value until 2050 in case of population increase. As 298 mentioned before, I used as targets overall infrastructure system-wide material stock values 299 consistent with high access level for each infrastructure service. The target values I obtained 300 can't be added to avoid double counting. I could also have used as target a single value of 301 material stock per capita based only on countries that had access to all infrastructure ser-302 vices. However, I rather chose to analyse each infrastructure services independently in order to 303 highlight those where a high access target in the short term is consistent or inconsistent with 304 low-carbon trajectories. 305

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.

## <sup>313</sup> 2.3 Quantifying the production-based $CO_2$ emissions related to man-<sup>314</sup> ufacturing 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.

### 317 2.3.1 Steel production

The steel production is today mainly divided into two production routes, the blast furnace-basic 318 oxygen furnace (BF-BOF) and the electric arc furnace (EAF). In the conventional BF-BOF 319 route, iron ore and coke are melted in a blast furnace in order to reduce iron ore and obtain 320 pig iron. The latter is then converted to steel in the basic oxygen furnace. Instead of using 321 BOF, iron can also be refined into steel in an open hearth furnace (OHF) but this technology 322 is energy intensive and is used to a smaller extent (World Steel Association, 2016). Electric arc 323 furnace steelmaking uses scrap steel as the main feed material. Direct reduced iron (DRI) can 324 also be used in electric arc furnace, the iron ore being reduced by a gas produced from natural 325 gas or coal. 326

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.

### 346 2.3.2 Cement production

<sup>347</sup> Cement manufacturing can be separated into two distinct stages. The first stage is producing <sup>348</sup> clinker by limestone calcination reaction in a rotating kiln. This chemical reaction releases  $CO_2$ <sup>349</sup> in itself, which is referred to here as process emissions. Process emissions represent the major <sup>350</sup> part of cement emissions and depend on the amount of clinker contained in one ton of cement, <sup>351</sup> 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.

### <sup>371</sup> 2.3.3 Trade structure

I aim to calculate producing-based  $CO_2$  emissions to be able to compare the results with 372 national or regional carbon budgets. This calls for representing in the modelling framework the 373 trade structure to allocate  $CO_2$  emissions to the producing countries for each ton of cement and 374 steel used in a given country. The trade ratio - the ratio of traded products weight and global 375 production weight - highlights which materials are particularly concerned by trade flow and 376 imported or exported emissions. For pig iron, an intermediate product of steel manufacturing, 377 the trade ratio was 8% in 2015 (World Steel Association, 2016) and for cement products 5%378 (UNSD, 2018; Van Oss, 2016). Cement is a commodity consumed mostly locally because of 379 high transportation costs (Cao *et al.*, 2017). I assumed the related trade effects associated on 380 emissions for these products are negligible. I considered here one ton of cement produced in 381 a country is consumed in the same one following Hache *et al.* (2020) and Denis-Ryan *et al.* 382 (2016).383

Conversely, the 2015 value of trade ratio for crude steel is 30% highlighting potential im-384 ported or exported emissions. To represent the steel trade structure, I first extracted from 385 BACI database (Gaulier & Zignago, 2010) the imports and exports flows in weight of steel 386 primary products for the year 2015 and for 207 countries. The commodity HS codes considered 387 are from 7206 to 7306 following the World Steel Association guidelines (World Steel Associa-388 tion, 2011). I then summed all the steel flows from one country to another and built a bilateral 389 trade matrix where each element (i,j) represent the aggregated weight of steel primary products 390 imported by the country i from the country j. I then incorporated in the matrix diagonal the 391 domestic consumption assuming it as equal to the steel production minus the steel exports (in 392

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 determi nants

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 406 trade structure as constant for all scenarios but alternatives could be done which will change 407 the allocation of producing-based  $CO_2$  emissions. Carbon intensities of production values in 408 2030 and 2050 are based on the  $2^{\circ}C$  (2DS) and the Beyond  $2^{\circ}C$  (B2DS) scenarios trajectory 409 (IEA, 2017b, 2018) for respectively the median2C and the below2C alternatives. The 2DS 410 scenarios refers to a  $CO_2$  emissions trajectory consistent with at least a 50% chance of limiting 411 the average global temperature increase to 2°C by 2100, with cumulative emissions of 1 170 Gt 412  $CO_2$  between 2015 and 2100. The B2DS cumulative emissions from the energy sector of around 413 750 Gt  $CO_2$  between 2015 and 2100, which is consistent with a 50% chance of limiting average 414 future temperature increases to  $1.75^{\circ}$ C. The emissions reduction relies on using best available 415 technologies to improve overall energy efficiency and deploying  $CO_2$  capture technologies. It 416 also implies for steel production to increase the global share of steel production for EAF route-417 both from scrap-based and DRI-based- to more than 50% and for cement production to decrease 418 the clinker ratio. I assumed for all countries a linear evolution of carbon intensity from 2015 to 419 2030 and from 2030 to 2050. 420

To project the evolution of the carbon intensity of electricity, I use the average values in 421 2050 extracted from the low carbon scenario database ADVANCE (Luderer et al., 2018; Vrontisi 422 et al., 2018), which is described in more detail in the next section. Data are disaggregated 423 across 5 major world regions and for different levels of climate ambition. Following Audoly 424 et al. (2018), I defined the carbon content of electricity as the ratio between the emissions 425 from the power sector and the total electric energy produced by the power sector. Values are 426 based on the Med2C and the WB2C scenarios of the ADVANCE database for respectively the 427 median2C and the below2C alternatives. In these scenarios, the carbon content can be negative 428 because the emissions reported for the electricity sector are those related to fossil combustion as 429 well as the negative emissions related to the use of bio-energy with carbon capture and storage 430 (BECCS). Other indirect emissions exist throughout the life cycle for each electricity generation 431 technology (Pehl et al., 2017). However, considering them would goes beyond the scope of the 432 paper and would induce double counting of emissions because they include emissions used to 433 produce steel or cement in the electricity generation capital. I assumed for all countries a linear 434 evolution of carbon content of electricity from 2015 to 2050. For countries with carbon contents 435 in 2015 lower than the projected regional values in 2050, the carbon content is assumed to be 436 437 constant.

## 438 3 Results and discussion

439 Some results are presented in this section following the format *median value (lower value-*440 *upper value)* based on the different target values of in-use stock per capita tested to integrate
441 uncertainties (see section 2.2 for description).

### 442 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 consid-447 ered. On one hand, the global in-use material stock-both cement and steel aggregated-increases 448 by a median value close to 10% on the period 2015-2030 to reach high access levels to water 449 or electricity. Cumulative material demands equal to 7.9 (5.7-10.5) Gt of cement and 1.49 450 (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 451 electricity. On the other hand, for transportation access, the aggregated in-use stock increase 452 by a median value of 50% with material demands reaching 49.9 (28.2-73.3) Gt of cement and 453 6.3 (2.8-16.9) Gt of steel. Sanitation and shelter infrastructures give intermediary results with 454 global in-use material stock increasing by a median value of 26%. In the modelling framework, 455 global population increases by 15% from 2014 to 2030 which highlight the high contribution of 456 access provision for sanitation, shelter and transport infrastructures. 457

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 465 represent more than 90% of global demand regardless of the infrastructure considered (figure 466 3). Within these regions, material demand is unevenly distributed across countries (figure 4). 467 Some countries contributes particularly to the global demand such as India, Nigeria, Indonesia, 468 Pakistan, Bangladesh, Ethiopia, Congo Dem.Rep, the Philippines and Tanzania where mate-469 rial needs are greater than 1 Gt to reach high access levels to transportation infrastructures. 470 One factor is the high population growth over the period 2015-2030, ranging from 21 million 471 inhabitants for Tanzania to 235 million inhabitants for India. Achieving high levels of access 472 in 2030 appears as a challenge in MAF if looking at the relative growth of the in-use material 473 stocks. Water and electricity access, which are the less material intensive objectives, induce a 474 stock multiplication by a factor greater than 15 in Madagascar, Ethiopia, Niger, Tchad, Central 475

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

I compare the cumulative material consumptions I estimated with existing scenarios of global 477 steel and cement production on the same period (van Ruijven et al., 2016; Edelenbosch et al., 478 2017; Winning et al., 2017; IEA, 2018). I filtered out only baseline scenarios - continuation of 479 past trends regarding the implementation of climate policies or energy/material efficiencies -480 to be consistent with my estimations. I obtained cumulative values of material either directly 481 from the text or by graphical reading using the software Web Plot Digitizer available at https: 482 //apps.automeris.io/wpd/. In these scenarios, demand for materials is related to economic 483 activity and population without consideration of infrastructure needs. 484

The material demand for providing high access to water, electricity and shelter is consistent 485 with these scenarios. The associated global cement and steel demands represent in the median 486 cases respectively at most 35-40% and 10-15% of literature values. If I consider the case of 487 reaching a quasi universal access with a 95% access rate, material needs are as expected higher 488 but still consistent with the existing scenarios in the median cases (figure 3). The consistency 489 of our results with global material production scenarios is less clear, to a smaller extent for 490 sanitation and to a larger extent for transport. It is all the less obvious as I did not consider 491 the cement and steel needed to maintain the capital already installed in 2014, which would lead 492 to additional material needs, particularly in developed countries. For sanitation, it depends on 493 the assumption about the target value of the in-service cement stock per capita. Considering 494 the upper bound leads to a cumulative demand representing 73-84% of literature values. For 495 transportation, median material needs reach the shares of 70-80% for cement and 22-32% for 496 steel compared to values of scenarios from literature. The upper values estimated are even at 497 a similar level for steel and above for cement. In the case of an access rate targeted of 95%, 498 median cumulative demands for both materials are more than doubled increasing to levels 490 higher than any existing values from literature. It calls into question the realism of achieving 500 a high access level to transportation at the global scale in 2030. 501

### <sup>502</sup> 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 508 primary energy conversion into electricity used during the manufacturing process - on the period 509 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. 510 Assuming that the access rate is kept at a high level until 2050, cumulative emissions for 511 the 2015-2050 period range from 10.3 (6.9-20) Gt  $CO_2$  for electricity to 53 (29.5-99.1) Gt 512  $CO_2$  for transportation. The major part of emissions come from cement production which 513 represents in baseline scenarios between 67% and 85% of global cumulative emissions depending 514 on the infrastructure considered. For median2C and below2C scenarios, the values obtained 515 for transportation - the most material-intensive access objective-decrease to respectively 45.6 516 (25.1-82.9) and 39.5 (21.7-72.2) Gt  $CO_2$ . 517

These results are low compared to most of literature on emissions induced by global in-518 frastructure development (Table 7) for different reasons. Contrary to Lamb & Rao (2015) and 519 Krausmann et al. (2020), I only focus on emissions from the steel and cement sectors. Also, 520 projections of steel and cement consumption are not driven by GDP (van Ruijven et al., 2016; 521 Krausmann et al., 2020) or by a convergence of stocks towards richest countries levels (Müller 522 et al., 2013; Krausmann et al., 2020) but by a convergence of stock to sufficient levels to as-523 sure high infrastructure access. Conversely, our results for transport are much higher than 524 those of Wenz et al. (2020) where authors assessed the material requirements and associated 525 emissions specific to road infrastructure to provide basic transportation access. In contrast to 526 this bottom-up and purely normative approach, my methodology here is more descriptive and 527 analyses, in the light of past trends, how the stocks of cement/steel in infrastructure could 528 increase across the whole economy by extending road access to all. The difference between the 529 results is all the more important as, I highlighted before, in most countries high access level 530

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 533 to Paris Agreement targets. Carbon budgets available to achieve the 2°C or the 1.5 °C targets 534 (66% chance) are respectively 1170 and 420 Gt  $CO_2$  from 2018 (Rogelj et al., 2018). Adding 535 the 106 Gt CO2 that have been emitted from 2015 to 2017 (Project, 2019), I obtained  $C0_2$ 536 budgets of 1276 and 526 Gt  $CO_2$  from 2015. Considering the most pessimistic case- reaching 537 a 90% transport access level in 2030 in baseline scenarios and assuming the upper target of 538 in-use material stock per capita - would consume from 2015 to 2050 about 8% and 19% of the 539 budgets available from 2015 to respectively achieve the  $2^{\circ}C$  and the  $1.5^{\circ}C$  targets. 540

I also analyse the consistency at finer geographical and sectoral scale between the emissions 541 I quantified and the existing  $CO_2$  emissions pathways (figure 5). I use as reference low-carbon 542 scenarios from the ADVANCE database (Luderer et al., 2018; Vrontisi et al., 2018). In this 543 database, nine integrated assessments models have produced a set of global climate policy 544 pathways consistent with limiting temperature increase in the 1.5-2°C range with different 545 levels of short-term ambition. This database has also the advantage of giving quantification 546 of  $CO_2$  emissions in the industrial sector - both process and direct emissions from energy 547 consumption - at the global scale and at a 5 world regions disaggregation (see section 3.1 for 548 regions description). 549

To be able to compare my results with the ADVANCE scenarios database, I first excluded 550 in this part the indirect emissions - emissions induced by the conversion of primary energy 551 into electricity used- which are aggregated to the electricity sector emissions in the ADVANCE 552 database. Secondly, in order to have an order of magnitude of cement and steel sectors emissions 553 in the database scenarios, I assumed that their share in the total industry sector emissions were 554 similar over time and between the five world regions. The cumulative emissions of the industry 555 sector extracted from the ADVANCE database scenarios were therefore multiplied by 0.55556 following IEA (2017b). Finally, to be consistent with the decarbonisation scenarios I applied 557 for the cement and steel sectors in the modelling framework, I selected in the ADVANCE 558 database (i) the 2020 Med2C and 2030 Med2C scenarios as comparison references for the 559

median2C estimations and (ii) the 2020 WB2C and 2030 WB2C scenarios as comparison 560 references for the below2C estimations. In the 2020 Med2C scenarios, mitigation efforts are 561 strengthened after 2020 to limit cumulative 2011-2100 CO2 emissions to 1600 GtCO2, leading 562 to more than 50% to stay below  $2^{\circ}$ C. In the 2020 WB2C scenarios, mitigation efforts are 563 strengthened after 2020 to limit cumulative 2011-2100 CO2 emissions to 1000 GtCO2, leading 564 to more than 67% chance of staying below 2°C. In the 2030 Med2C, after implementing the 565 NDCs without strengthening until 2030, mitigation efforts are strengthened to obtain the same 566 cumulative emissions as in the 2020 Med2C. In the 2030 WB2C scenarios, after implementing 567 the NDCs without strengthening until 2030, mitigation efforts are strengthened to obtain the 568 same cumulative emissions as in the 2020 WB2C. 569

According to figure 5, providing globally a high level of access to the five infrastructures 570 considered in this study leads to emissions related to cement and steel requirements lower than 571 the cumulative emissions of these sectors from the ADVANCE low-carbon scenarios on the same 572 period. This result is also valid for the world regions ASIA, LAM, OECD and REF where the 573 cumulative emissions resulting from this modelling represent a maximum of 67% of cumulative 574 emissions from the corresponding reference scenarios (figure 5). However, for the MAF region, 575 providing a high level of access to sanitation and transportation induces emission levels that are 576 of the same magnitude order than some estimations of the ADVANCE corresponding scenarios. 577 For transportation, our median estimates are even above the lower bounds of the ADVANCE 578 scenarios estimations regardless of the climate ambition level. 579

## 580 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 590 of access rate is associated with a high increase of material stocks and that (ii) infrastructure 591 access tends to follow a sequencing process along material stocks increase with electricity and 592 water coming first, and transportation access last. I show cement and steel demand associated 593 with providing in 2030 global high access level (90%) would be concentrated in Asia and Middle-594 East & Africa regions. In this latter region, achieving high access level in 2030 appears as 595 challenging if looking at the relative growth of the cement and steel stocks. For water, electricity 596 and shelter access, I find global cement and steel requirements are consistent with existing 597 global projections of cement and steel production. I obtain on the contrary less consistent 598 results to a smaller extent for sanitation and to a larger extent for transportation. This calls 599 into question the realism of achieving high levels of access to these infrastructures in the short 600 term. I find global cumulative embodied emissions from 2015 to 2050 from cement and steel 601 requirements would represent small shares of the carbon budgets associated with the Paris 602 agreement objectives. Assuming relative decoupling of cement and steel production from  $CO_2$ 603 emissions following existing industry roadmaps, I find on the same time period lower cumulative 604 emissions than those of the steel and cement sector from existing low-carbon pathways, at the 605 global scale and for four world regions over five. However this result doesn't stand for sanitation 606 and transportation access in the Middle-east & Africa region. 607

This work has some limitations related to the chosen methodology. First, I based this study 608 on infrastructure access indicators which, like all indicators, have their limits. For example, 609 for transportation, the indicator only relates to the geographical proximity of the road network 610 and says nothing about the availability of vehicles for the effective use of the network or about 611 the modal split allowing the satisfaction of human welfare for all. Second, I assumed the 612 trade structure evolution constant which could be refined in order to assess the effects of heavy 613 industries relocation or taxes on imported materials, as the United States recently did on 614 Chinese steel. Third, potential influencing factors of technology production choice such as 615

capacity installed, production price or steel scrap availability should be integrated in futureresearch.

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 625 demand and  $CO_2$  emissions, assuming countries would only focus on providing access to the 626 whole population, in a purely normative approach. My methodology here is more descriptive 627 in order to analyse, in the light of past trends, how countries could increase their stocks of 628 cement/steel in infrastructure across the whole economy by extending access to all. It com-629 plements a bottom-up approach in four ways. First, it takes into account the chronology of 630 access in development (e.g., access to transport comes after access to electricity and water). 631 Second, infrastructure can be considered as a 'system-of systems' in which different types of 632 infrastructure act in concert to deliver services (Hall et al., 2016) and my methodology allows 633 to integrate this interdependence at the level of the economy (e.g., a certain level of transport 634 infrastructure is needed to provide access to water). Finally, it takes into account the influence 635 of current socio-political configurations which can induce an infrastructure stock growth that 636 is not necessarily 'basic-needs oriented' but support increasing use among those with access. 637

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; <sup>645</sup> van den Berg *et al.*, 2019).

A second interpretation is that relying solely on the decarbonisation of the steel and cement 646 sectors is not enough to achieve the goals of access to basic infrastructure services by 2030 647 without compromising the climate mitigation targets. Other levers must therefore be used 648 in the short term. Material efficiency is a first significant opportunity decreasing the cement 649 and steel consumption for the same infrastructure services. It could take different forms as 650 a more intensive use of existing capital (lifetime extension, reducing per capita floor area...) 651 or the reuse of steel and cement components (Hertwich et al., 2019; Pongiglione & Calderini, 652 2014). Substitution to less intensive construction materials is another potential lever such as 653 using timber over steel and concrete in buildings construction (Churkina et al., 2020; Heeren 654 et al., 2015). More research is needed to understand the underlying drivers of cement and steel 655 accumulation along the development process to implement relevant policy instruments for lower 656 usage of cement and steel. 657

Climate policies can therefore make it possible to reconcile the satisfaction of essential needs 658 for infrastructure services and the reduction of  $CO_2$  emissions but only by ensuring a triad of 659 conditions: a fast decarbonisation of the steel and cement sectors, a reduction in the need 660 for steel and cement, and a strengthening of emission reduction efforts in developed countries. 661 The national determined contributions are currently inconsistent with the Paris Agreement 662 objective of limiting global average temperature increase to well below  $2^{\circ}C$  (Höhne *et al.*, 2020) 663 and should be enhanced during the 2023 global stocktake. This 'ratcheting-up' process will most 664 likely include some evaluation of fairness where the question of carbon emissions spaces to allow 665 'sufficient' development in developing countries should be be discussed. Also, the crucial role of 666 cement and steel sectors for sustainable development suggests that these sectors should be taken 667 out of national policy discussions and put at the heart of international climate negotiations in 668 order to foster cooperation between countries for inducing technological leapfrogging. 669

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963		1				
	Services	SDG target	Official indica-	Chosen indica-	Coverage	Source
			tor	tor		
	Electricity	7.1 Universal access to	Percentage of	Percentage of	214 coun-	World
		affordable, reliable and	population with	population with	tries, 1990-	Bank
		modern energy services	access to house-	access to house-	2014	(2018)
			hold electricity	hold electricity		
	Water	6.1 Universal and equi-	Proportion of	Percentage of	203 coun-	World
		table access to safe and	population using	population hav-	tries; 1990-	Bank
		affordable drinking wa-	safely managed	ing access to an	2015	(2018)
		ter for all	drinking water	improved water		
			services	source		
	Sanitation	6.2 Access to adequate	Proportion of	Percentage of	202 coun-	World
		and equitable sanita-	population using	population hav-	tries, 1990-	Bank
964		tion and hygiene for all	safely managed	ing access to	2015	(2018)
		and end open defeca-	sanitation ser-	improved sanita-		
		tion	vices	tion facilities		
	Shelter	11.1 Adequate, safe	Proportion of	Proportion of	96 coun-	World
		and affordable housing	urban population	urban population	tries; 2000,	Bank
		and basic services and	living in slum	not living in slum	2005, 2007,	(2018)
		upgrade slums	household	household	2009 and	
					2014	
	Transport	9.1 Develop quality,	Proportion of the	Proportion of	151 coun-	Mikou
		reliable, sustainable	rural population	population living	tries, 2014	et al.
		and resilient infras-	living within $2 \text{ km}$	within 2 km of an		(2019)
		tructure, including	of an all-season	all-season road		
		regional and trans-	road			
		border infrastructure				

Table 1:	Description	of in	nfrastructure	access	data
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In-use material	Coverage	Source
$\operatorname{stock}$		
Cement	184 countries. 1990-2014. All sec-	Cao <i>et al.</i> (2017)
	tors aggregated	
Steel	139 countries. 1990-2008. Sec-	Pauliuk et al. (2013)
	tor "buildings-construction-	
	infrastructure"	

Table 2: Description of in-use material stock data. I assumed in-use steel stock equal to in-use <sup>967</sup> 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	In-use stock per	In-use stock per	Underlying assumptions
rate in	capita in 2014	capita targeted	
2014			
< 90%	<global median<="" th=""><th>Global median</th><th>Countries are still in the development process</th></global>	Global median	Countries are still in the development process
	value associated	value associated	so the in-use stocks per capita will increase.
	with a $90\%$ access	with a $90\%$ access	
	rate	rate	
$<\!90\%$	>Global median	2014 value	Countries with access rates below 90% are
	value associated		still in the development process so the in-use
	with a $90\%$ access		stocks per capita will not decrease
	rate		
> 90~%	<global median<="" th=""><th>2014 value</th><th>Country specific conditions allows lower in-</th></global>	2014 value	Country specific conditions allows lower in-
	value associated		use stocks levels per capita than global me-
	with a $90\%$ access		dian value to provide high infrastructure ac-
	rate		cess. In-use stocks levels per capita will sat-
			urate in developed countries.
>90%	>Global median	Global median	Country specific conditions lead to higher in-
	value associated	value associated	use stocks levels per capita than global me-
	with a $90\%$ access	with a $90\%$ access	dian value to provide high infrastructure ac-
	rate	rate	cess. In-use stocks levels per capita can de-
			crease 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 <sup>973</sup> been calculated using data from Morfeldt *et al.* (2015) and Milford *et al.* (2013)

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

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

		baseline	median2C	below2C	
977	Grid emissions	Constant	2050 : From -35 to 54 gCO2/kWh	2050 : From -89 to -10 gCO2/kWh	
		Constant	Differing on world regions	Differing on world regions	
	Trade structure	Constant	Constant	Constant	
	Direct cement	Constant	2030 : 0.52 t $CO_2/{\rm t}$ cement	2030 : 0.41 t $CO_2/{\rm t}$ cement	
	emissions	Constant	2050 : 0.37 t $CO_2/{\rm t}$ cement	2050 : 0.2 t $CO_2/{\rm t}$ cement	
	Direct steel emis-	Constant	2030 : 1 t $CO_2/{\rm t}$ cement	$2030$ : 0.7 t $CO_2$ /t cement	
	sions	Constant	2050 : 0.7 t $CO_2/{\rm t}$ cement	2050 : 0.33 t $CO_2/{\rm t}$ cement	

Table 6: Evolution of parameters in the different scenarios of cement and steel sectors decar-978bonisation



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