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

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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

22 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

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 through 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).

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

65 Yet, manufacturing the construction materials required for infrastructure is an important
66 source of greenhouse gas emissions. The emissions embodied in materials account for over 90%
67 of lifecycle emissions in infrastructures (Huang *et al.*, 2018) and emissions from the construction
68 of new urban infrastructure could represent 27.5% of total urban emissions between 2016 and
69 2030 (Creutzig *et al.*, 2016). Mitigating these embodied emissions are crucial to reach carbon
70 neutrality.

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

76 Their contribution to global CO_2 emissions is expected to continue in the short-term for two
77 reasons. First of all, process emissions resulting from chemical reactions involved to manufacture
78 materials are difficult to eliminate without carbon capture and storage technologies (Davis *et al.*,
79 2018). Secondly, the technical lifetimes of the capital used in the heavy industries are between
80 30 and 40 years, creating inertia in the renewal of technologies and slowing possibilities to
81 reduce emissions (Erickson *et al.*, 2015). A rapid increase of the global infrastructure stock in
82 the short term could then consume a significant part of the carbon budget available to meet

83 the Paris Agreement targets (Krausmann *et al.*, 2020; Müller *et al.*, 2013).

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

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

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

112 would consume a significant part of the carbon budget available to stay below 2°C. Although,
113 the convergence of developing countries to infrastructure level of wealthiest countries would
114 be associated with higher access level to basic infrastructures, this objective is questionable
115 because of potential negative outcomes such as land take (Colsaet *et al.*, 2018) and it could not
116 induce significant progress for countries with already high access rates (O'Neill *et al.*, 2018; Rao
117 *et al.*, 2014). Krausmann *et al.* (2020) has recently estimated the embodied CO_2 emissions - all
118 materials considered - for a global convergence at the per-capita level of in-use stocks that the
119 developed countries had achieved in 1970, considering it as 'sufficient' in terms of life quality.
120 Authors highlighted large reductions in global resource demand and emissions compared to the
121 scenario where countries converge to the current infrastructure level of industrialized countries.

122 Few studies have focused on the carbon/energy embodied in construction materials to pro-
123 vide access to basic infrastructure. Two studies have bottom-up estimated using life cycle
124 analysis and input-output tools the energy needs - including the energy used in building some
125 basic infrastructure - to provide decent material living standards to the full population in three
126 countries (Rao *et al.*, 2019) and at the global scale (Millward-Hopkins *et al.*, 2020). Wenz *et al.*
127 (2020) quantified the cumulative embodied CO_2 emissions associated with building global road
128 network to provide universal access to road.

129 In this paper, I first use historical data to describe the global trends of access to 5 basic
130 infrastructure services - electricity, water, sanitation, shelter or transport - in relation to the
131 steel and cement embodied in infrastructure stocks. Then, following historical patterns, I
132 quantify the amounts of cement and steel needed in each country associated with reaching
133 high access levels in 2030 and kept access levels high until 2050 for each of the infrastructure
134 services. Finally, I estimate the cumulative CO_2 emissions from manufacturing cement and
135 steel requirements. I discuss my findings with respect to the available carbon budgets and the
136 existing scenarios of material production and greenhouse gas emissions in the cement and steel
137 industries.

138 This study goes beyond the existing literature in different aspects. First, I assess the material
139 and carbon impact of achieving 5 sustainable development goals related to infrastructure access.
140 Then, I take into account country-specific determinants of cement and steel consumption such

141 as trade structure and carbon intensity of material production to calculate production-based
142 CO_2 emissions. Finally, I use 3 decarbonization scenarios of the cement and steel industries (i) to
143 assess how the projected low-carbon transition in these industries limits the carbon impact of
144 providing infrastructure access and (ii) to disentangle the contributions to emissions pathways
145 from changes in the carbon intensities of material production and in the material demands.

146 The rest of this article is structured as follows: Section 2 describes the methodology, Section
147 3 presents the results and discussion and Section 4 provides a summary and a conclusion.

148 2 Methodology

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

157 2.1 Analysing trends in infrastructure access levels along the in-use 158 material stocks build-up

159 2.1.1 Data and definitions

160 I chose to focus on 5 basic infrastructure services - water, electricity, shelter, sanitation and
161 transportation. In the human needs theory, they are essential needs satisfiers contributing
162 through different channels to personal autonomy and physical health (Gough, 2015). Access
163 definition is more straightforward than other infrastructure services such as health or education
164 (Steckel *et al.*, 2017) and data are available over several years and countries (Table 1). The
165 infrastructure associated is capital-intensive and requires cement and steel (see Du Fei *et al.*
166 (2013) for water and sanitation systems, Anastasiou *et al.* (2015) for road network or Bumby

167 *et al.* (2010) for power distribution).

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

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

180 At least 50 litres per person per day are needed to ensure hygiene including laundry and
181 domestic cleaning. Inadequate access to safe drinking water is associated with diarrhoea dis-
182 ease and exposure to chemical pollutants (Hunter *et al.*, 2010). This is related to the SDG
183 6.1 “*Universal and equitable access to safe and affordable drinking water for all*”. The official
184 indicator is the percentage of people using safely managed drinking water services. I used the
185 percentage of population having access to an improved water source such as piped household
186 water, public tap, tube well/borehole, protected dug wells, protected springs or rainwater col-
187 lection. This indicator is close in definition to the official one and has better geographical and
188 temporal coverages.

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

196 indicator is close in definition and has better temporal and geographical coverages.

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

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

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

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

226 **2.1.2 Patterns of infrastructure access**

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

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

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

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

257 Figure 2 presents the distribution of in-use cement and steel stocks per capita for the 20
258 countries with the access level closest to 90%. The median values differ between infrastructure
259 type and materials to achieve high access rates. Values are higher for cement than steel for all
260 infrastructures considered, with a factor ranging from 6 for water to 12 for shelter. While the
261 lowest values obtained are for electricity with 4.53 tons of cement per capita and 0.46 ton of
262 steel per capita, these values are the highest for transportation reaching respectively 13.08 tons
263 of cement per capita and 1.75 ton of steel per capita. Infrastructure access tends to follow a
264 sequencing process along material stocks increase with electricity and water coming first, and
265 transport access last, which is in line with previous results (Steckel *et al.*, 2017). For the year
266 2014, only 10 countries reach an access rate to sanitation services without having done the
267 same for either electricity or water. 8 countries reach an access rate to transportation higher
268 than 90% without having done the same on one of the other infrastructure.

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

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

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

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

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

306 I did not integrate capital depreciation here so the material needs obtained should be con-
307 sidered as lower bounds. I used national population projection from the Shared Socioeconomic
308 Pathway 2 (SSP2) scenario (O'Neill *et al.*, 2017). It is a medium scenario with global popula-
309 tion increasing from 6.9 billion people in 2005 to more than 9 billion people in 2050 (Kc & Lutz,

310 2017). Using this population scenario also allows to compare my quantifications of material
311 needs and carbon emissions with the literature. I assumed linear evolution of national in-use
312 material stock towards targeted stock.

313 **2.3 Quantifying the production-based CO_2 emissions related to man-** 314 **ufacturing cement and steel**

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

317 **2.3.1 Steel production**

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

327 The four steel production routes (BF-BOF, BF-OHF, scrap-EAF and DRI-EAF) differ in
328 terms of energy consumption and CO_2 emissions (Morfeldt *et al.*, 2015). I synthesised in Table
329 4 the related direct CO_2 emissions and the electricity consumption. I considered here emissions
330 from raw material preparation processes (sintering and coking) to rolling processes using mill
331 to be consistent with the decarbonisation scenarios of the steel sector I used (see subsection
332 2.3.4).

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

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

340 The calibration is consistent with previous estimations. Hasanbeigi *et al.* (2016) obtained
341 for the year 2010 CO_2 emissions intensity of production equal to 2.15 t CO_2 /ton steel for
342 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
343 for U.S.A. My corresponding calibrated values are respectively 2.19, 1.73, 1.40 and 1.12 t CO_2 /t
344 steel. This suggests a change in the technology used to produce steel in Mexico and U.S.A.
345 from 2010.

346 2.3.2 Cement production

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

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

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

362 I estimated process, direct and indirect emissions to produce one ton of cement in each ce-
363 ment producing country. The World Business Council for Sustainable Development (WBCSD)
364 developed the Getting the Numbers Right (GNR) database synthesizing from 2005 to 2018

365 technical informations for more than 900 individual cement plants in different world regions. I
366 extracted for the year 2015 the regional average values of clinker ratio, carbon intensity of the
367 fuel mix, thermal energy consumption and cement plant power consumption (WBCSD, 2016).
368 I applied these values to each countries included in the related world regions. Process emissions
369 factor for clinker production was taken from Eggleston *et al.* (2006) and national CO₂ intensity
370 of grid from IEA (2017a). Data and sources are synthesized in table 5.

371 **2.3.3 Trade structure**

372 I aim to calculate producing-based CO₂ emissions to be able to compare the results with
373 national or regional carbon budgets. This calls for representing in the modelling framework the
374 trade structure to allocate CO₂ emissions to the producing countries for each ton of cement and
375 steel used in a given country. The trade ratio - the ratio of traded products weight and global
376 production weight - highlights which materials are particularly concerned by trade flow and
377 imported or exported emissions. For pig iron, an intermediate product of steel manufacturing,
378 the trade ratio was 8% in 2015 (World Steel Association, 2016) and for cement products 5%
379 (UNSD, 2018; Van Oss, 2016). Cement is a commodity consumed mostly locally because of
380 high transportation costs (Cao *et al.*, 2017). I assumed the related trade effects associated on
381 emissions for these products are negligible. I considered here one ton of cement produced in
382 a country is consumed in the same one following Hache *et al.* (2020) and Denis-Ryan *et al.*
383 (2016).

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

393 case of negative values, it was considered as null). I finally divided each line i by the apparent
394 consumption - domestic production minus exports plus imports - of the country i . Steel pro-
395 duction data was obtained from World Steel Association (2016). In each cell (i,j) , the obtained
396 value represents the share of country i consumption of steel primary products coming from the
397 country j .

398 **2.3.4 Scenarii used for the dynamics of the production-based emissions determi-** 399 **nants**

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

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

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

443 I estimated the steel and cement in-use stocks levels in line with providing globally high access
444 rates for each infrastructure service. To do so, I used for each country as targets of stocks per
445 capita either the value derived from global trends or the national stock per capita for the year
446 2014 (see methodology section for the different cases and underlying assumptions).

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

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

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

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

477 I compare the cumulative material consumptions I estimated with existing scenarios of global
478 steel and cement production on the same period (van Ruijven *et al.*, 2016; Edelenbosch *et al.*,
479 2017; Winning *et al.*, 2017; IEA, 2018). I filtered out only baseline scenarios - continuation of
480 past trends regarding the implementation of climate policies or energy/material efficiencies -
481 to be consistent with my estimations. I obtained cumulative values of material either directly
482 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
483 activity and population without consideration of infrastructure needs.
484

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

502 3.2 Embodied CO₂ emissions

503 I quantified the CO₂ emissions from the production of materials needed to reach high access
504 level to the different infrastructures in 2030 and also to keep this access level high until 2050
505 in case of population increase. To do so, I applied three scenarios of emissions mitigations
506 ambition in the cement and steel industries, described in the methodology section : *baseline*,
507 *median2C* and *below2C* scenarios.

508 For baseline scenarios, I obtain cumulative emissions - including indirect emissions from
509 primary energy conversion into electricity used during the manufacturing process - on the period
510 2015-2030 from 7.3 (4.6-15) Gt CO₂ for electricity to 42.3 (22.6-80.5) Gt CO₂ for transportation.
511 Assuming that the access rate is kept at a high level until 2050, cumulative emissions for
512 the 2015-2050 period range from 10.3 (6.9-20) Gt CO₂ for electricity to 53 (29.5-99.1) Gt
513 CO₂ for transportation. The major part of emissions come from cement production which
514 represents in baseline scenarios between 67% and 85% of global cumulative emissions depending
515 on the infrastructure considered. For *median2C* and *below2C* scenarios, the values obtained
516 for transportation - the most material-intensive access objective-decrease to respectively 45.6
517 (25.1-82.9) and 39.5 (21.7-72.2) Gt CO₂.

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

531 for transportation tends to be achieved after having already reached a high level of access to
532 water, electricity, sanitation and shelter.

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

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

550 To be able to compare my results with the ADVANCE scenarios database, I first excluded
551 in this part the indirect emissions - emissions induced by the conversion of primary energy
552 into electricity used- which are aggregated to the electricity sector emissions in the ADVANCE
553 database. Secondly, in order to have an order of magnitude of cement and steel sectors emissions
554 in the database scenarios, I assumed that their share in the total industry sector emissions were
555 similar over time and between the five world regions. The cumulative emissions of the industry
556 sector extracted from the ADVANCE database scenarios were therefore multiplied by 0.55
557 following IEA (2017b). Finally, to be consistent with the decarbonisation scenarios I applied
558 for the cement and steel sectors in the modelling framework, I selected in the ADVANCE
559 database (i) the *2020 Med2C* and *2030 Med2C* scenarios as comparison references for the

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

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

580 4 Conclusion

581 Manufacturing the cement and steel materials required for infrastructures is an important source
582 of greenhouse gas emissions. In this paper, I assess if high level of access to 5 basic infrastructure
583 services - electricity, water, shelter, sanitation and transportation - can be provided at the
584 global scale in 2030 and until 2050 without compromising climate mitigation targets. Following
585 historical patterns, I first quantify the cement and steel requirements in each country associated
586 with providing high access levels. I then estimate the production-based carbon dioxide emissions

587 related to manufacturing the cement and steel needs. To do so, I model influencing factors such
588 as national production technologies mix, trade structure and mitigation actions in the cement
589 and steel industries.

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

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

616 capacity installed, production price or steel scrap availability should be integrated in future
617 research.

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

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

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

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

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

658 Climate policies can therefore make it possible to reconcile the satisfaction of essential needs
659 for infrastructure services and the reduction of CO_2 emissions but only by ensuring a triad of
660 conditions: a fast decarbonisation of the steel and cement sectors, a reduction in the need
661 for steel and cement, and a strengthening of emission reduction efforts in developed countries.
662 The national determined contributions are currently inconsistent with the Paris Agreement
663 objective of limiting global average temperature increase to well below $2^\circ C$ (Höhne *et al.*, 2020)
664 and should be enhanced during the 2023 global stocktake. This ‘ratcheting-up’ process will most
665 likely include some evaluation of fairness where the question of carbon emissions spaces to allow
666 ‘sufficient’ development in developing countries should be discussed. Also, the crucial role of
667 cement and steel sectors for sustainable development suggests that these sectors should be taken
668 out of national policy discussions and put at the heart of international climate negotiations in
669 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 <i>et al.</i> (2019)

Table 1: Description of infrastructure access data

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

967 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).

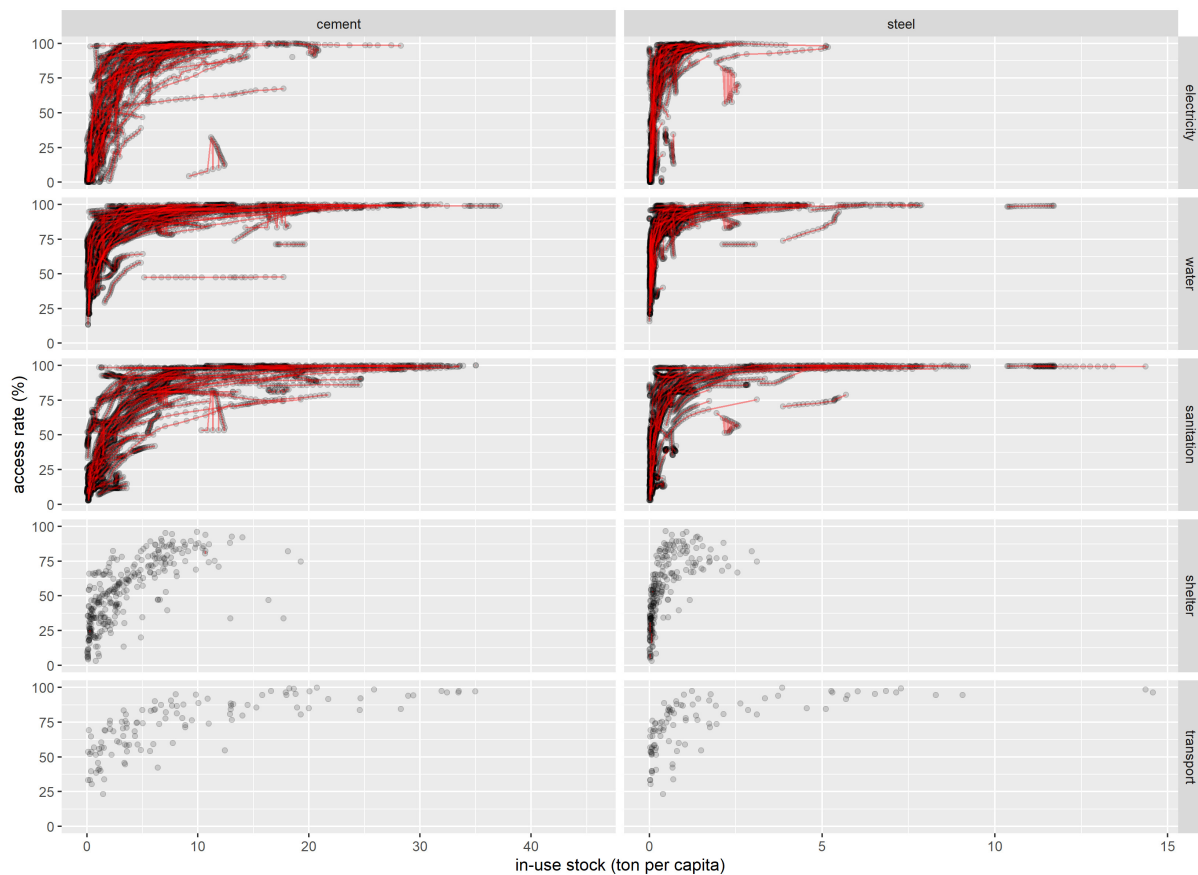


Figure 1: Scatter plots of infrastructure access rates against in-use material stocks. The samples have been filtered out by removing values of 0% and 100% access rates for readability purpose. Steel stock has been projected from 2008 to 2014, assuming the ratio of the cement stock growth rate to the 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.

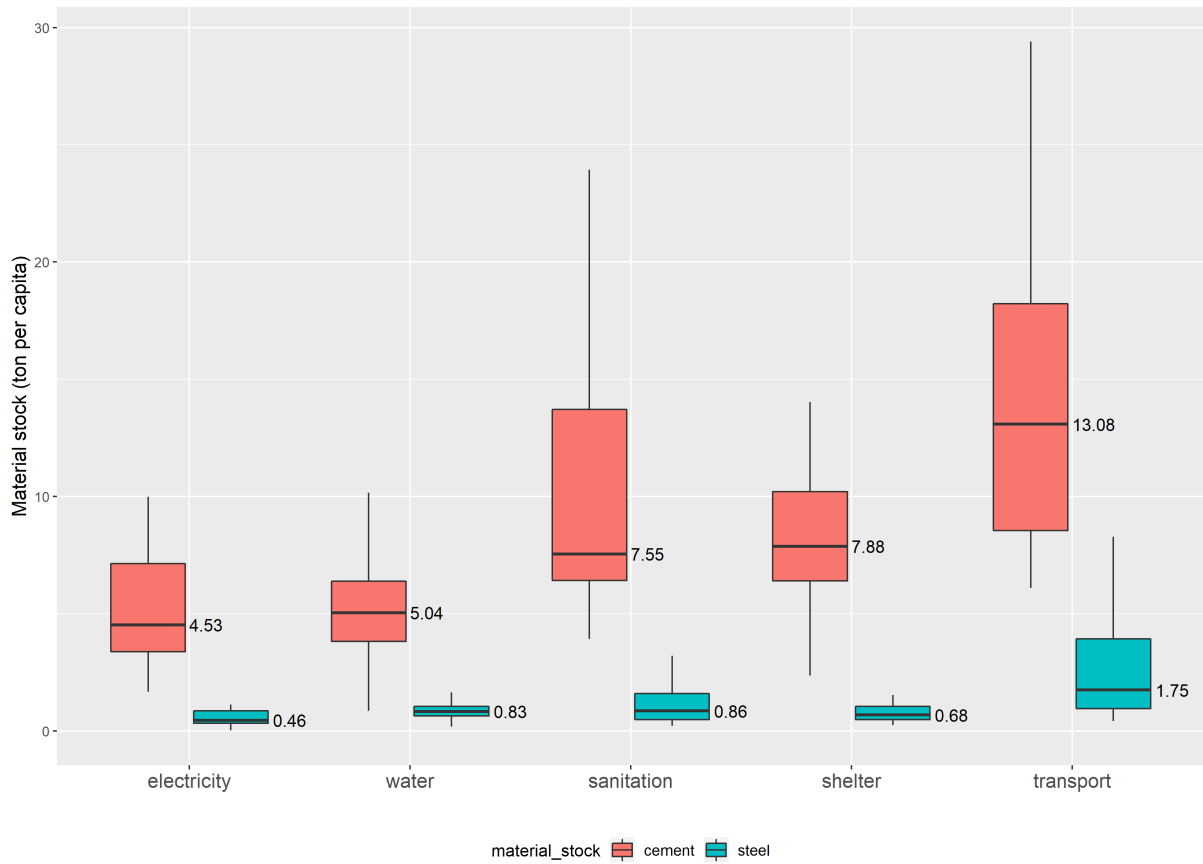


Figure 2: Distribution of in-use cement and steel stocks per capita for the 20 countries with the access rate closest to 90%. These values represent the materials embodied in the whole infrastructure stock and should not be considered as materials used specifically for a infrastructure type.

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

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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

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973 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 CO ₂ /t steel)	Morfeldt <i>et al.</i> (2015); Milford <i>et al.</i> (2013)	see Table 3 for calculated values
	Electricity intensity of the production routes (kWh/t steel)	Morfeldt <i>et al.</i> (2015); Milford <i>et al.</i> (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 CO ₂ /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 CO ₂ emissions factor (t CO ₂ /t clinker)	Eggleston <i>et al.</i> (2006)	

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

	baseline	median2C	below2C
<i>Grid emissions</i>	Constant	2050 : From -35 to 54 gCO ₂ /kWh Differing on world regions	2050 : From -89 to -10 gCO ₂ /kWh Differing on world regions
<i>Trade structure</i>	Constant	Constant	Constant
<i>Direct cement emissions</i>	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
<i>Direct steel emissions</i>	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

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

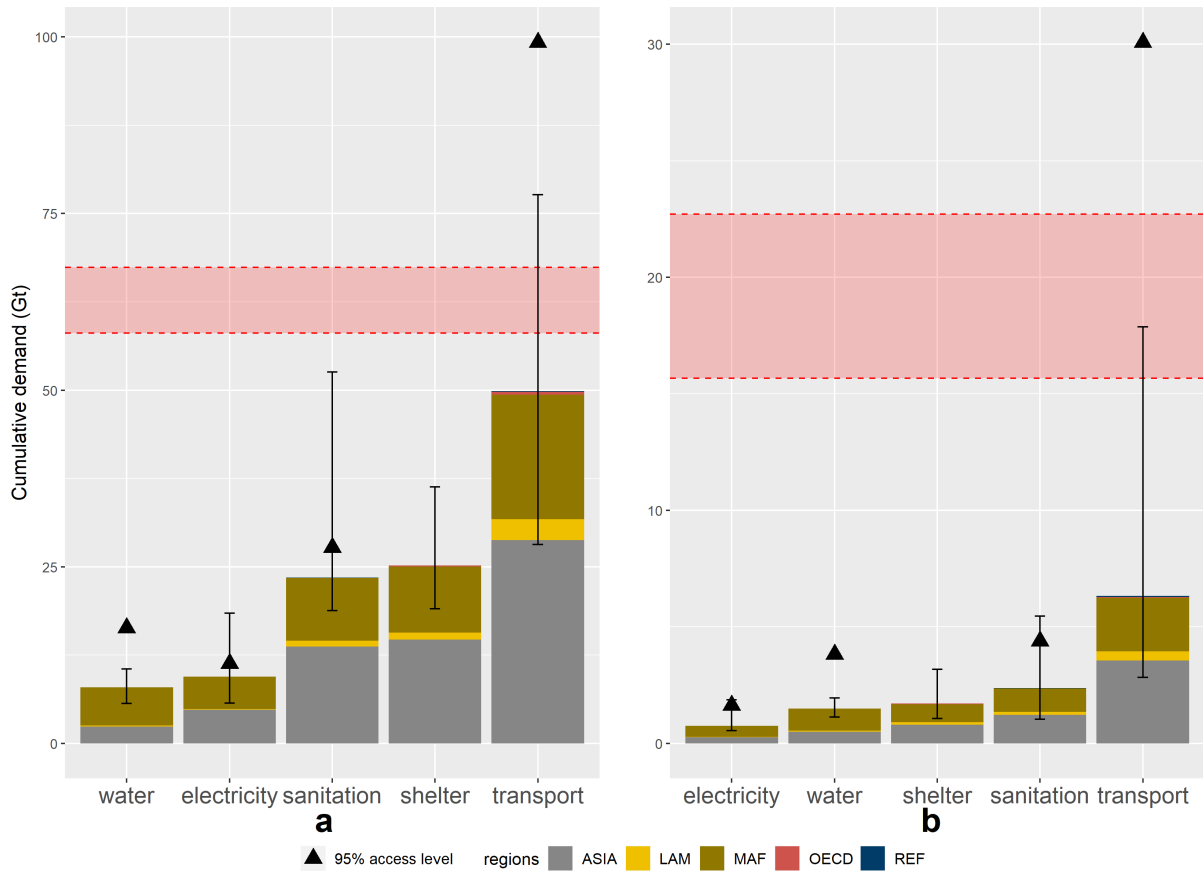


Figure 3: Global cumulative material demand of cement (a) and steel (b) from 2015 to 2030 associated with meeting high access rate (90%) to different infrastructures. Material consumption levels are presented here in a sequential manner to be consistent with high access levels to the different infrastructure 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.

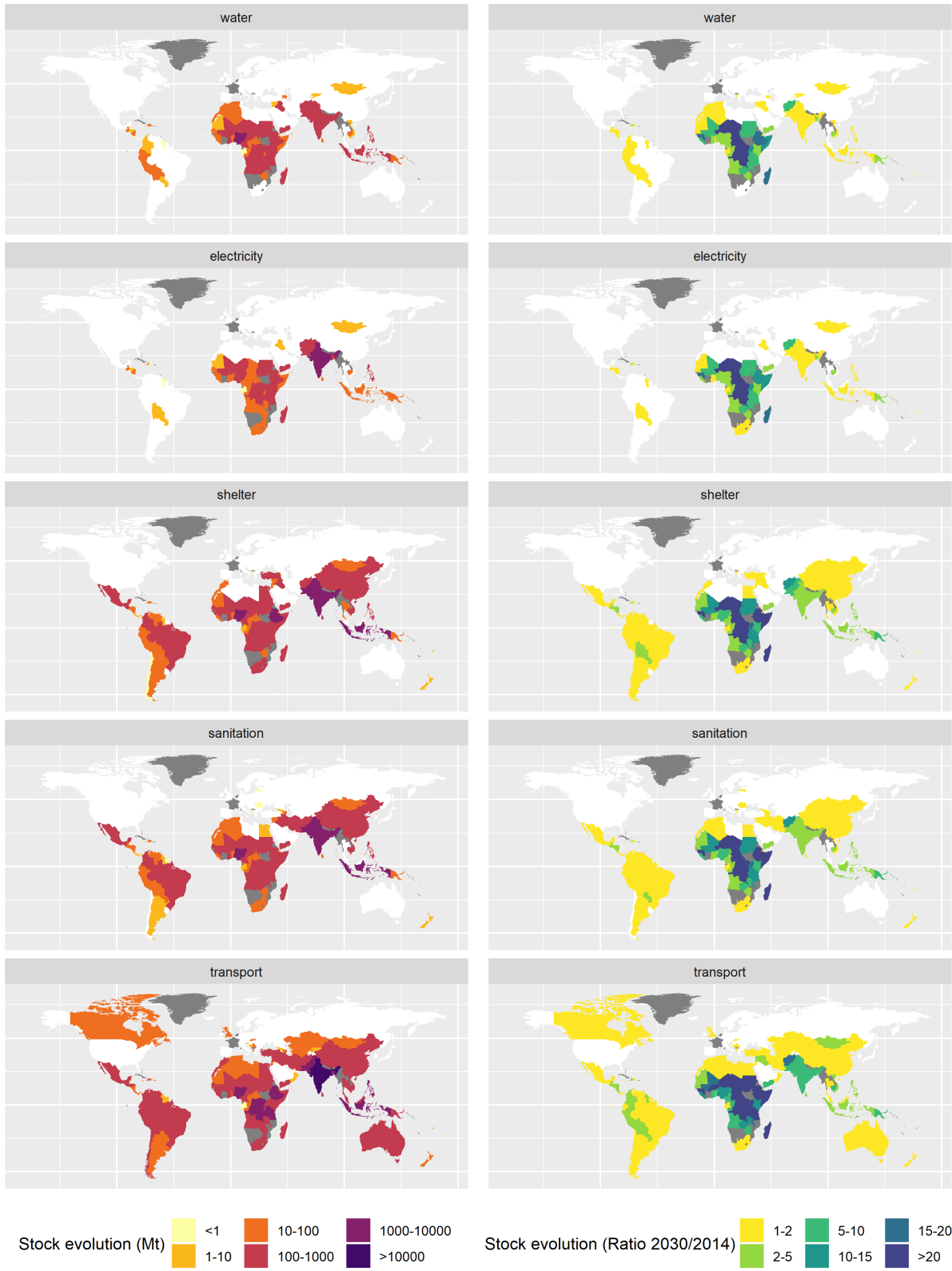


Figure 4: Net addition to material stock - cement and steel together - at national scale from 2015 to 2030 associated with reaching high infrastructures access

Study	Infrastructure	Emissions (Gt CO ₂)	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 <i>et al.</i> (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 <i>et al.</i> (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 <i>et al.</i> (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 <i>et al.</i> (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

980

981

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.

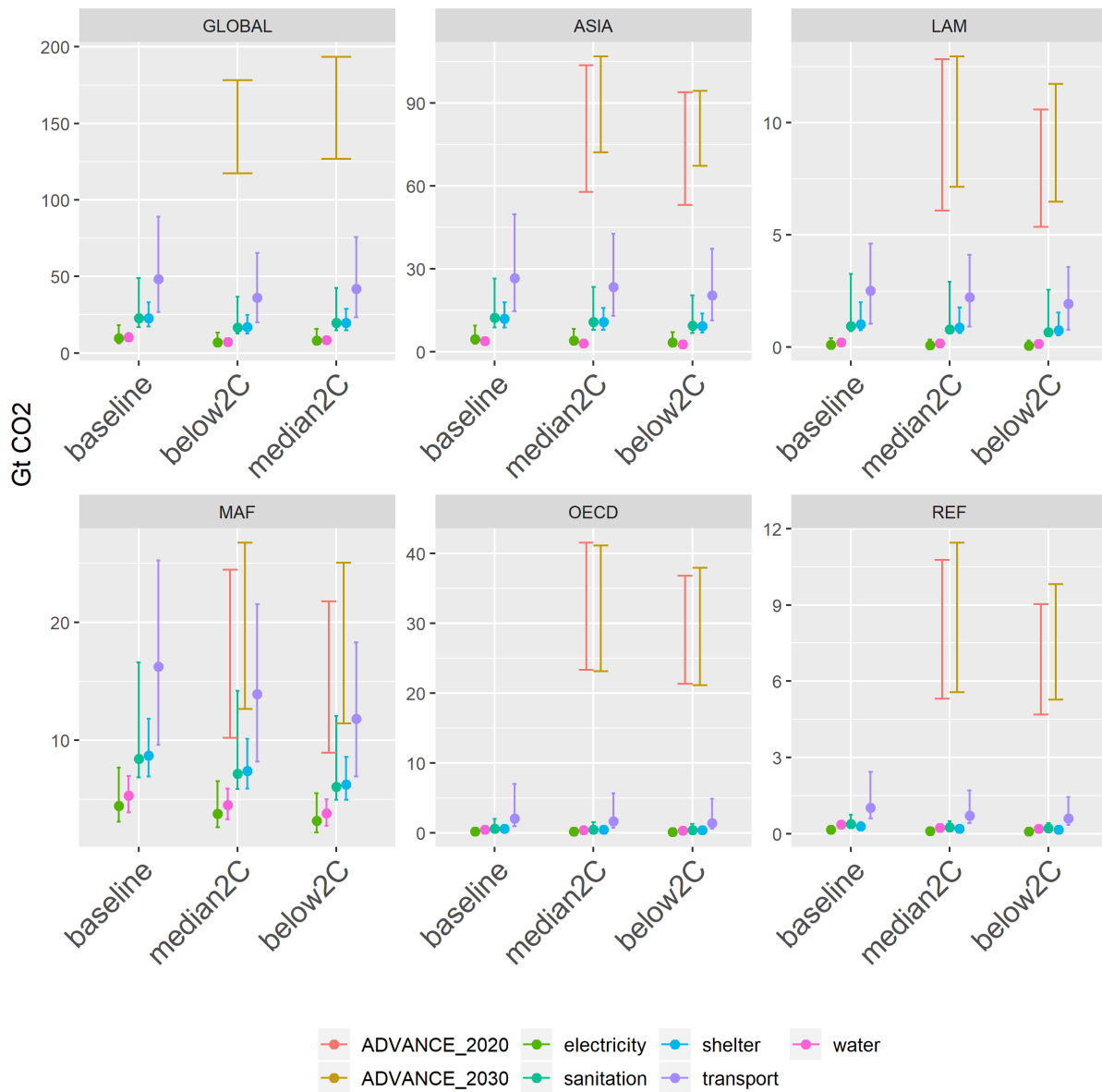


Figure 5: Cumulative emissions (direct and process-related) from 2015 to 2050 associated with the cement and steel requirements to reach a 90% access level. Points represent the central value of the estimations for each combination of infrastructure and mitigation ambition in the cement and steel sector. 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.