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Do we have enough natural sand for low-carbon infrastructure?

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<heading level 1> Abstract

Global low-carbon transition demands the development of large-scale infrastructure, which is sand-intensive. Natural sand is widely considered abundant, while recent research has pointed out the increasing risk of supply shortage in a number of world regions. In the current research, we examine the implication of future sand demand in the context of low-carbon infrastructure development. We mapped the projected investments on buildings and low-carbon infrastructure up to 2030, and estimated the sand intensity of the two types of construction. We translated these investments and sand intensity to country-specific sand demand projections under three economic development scenarios. Our results indicate that China is expected to face the highest sand demand, followed by India, and that should the current sand extraction rates and construction practices be maintained, developing countries will be exposed to a significant supply risk of construction sand. Under the scenario of sustainable growth, developed economies are expected to have a relatively stable sand demand while South-East Asia and Africa will see a rapid increase in their sand demand the

next 15 years. Our results call regional sand supply security into attention in low-carbon transition planning.

<heading level 1> Introduction

Industrialization, urbanization, economic development and population growth are expected to induce societal changes in the coming decades (Jiang and O'Neill 2017; KC and Lutz 2017; Crespo Cuaresma 2017). One of the sectors that will be significantly affected in the course of such changes is construction, which can be distinguished into infrastructure projects and into buildings for housing or office purposes. On the one hand, significant investments in infrastructure will be required as a result of the increased demand in key socio-technical services, such as energy and transportation demand and water and sanitation needs (Bergesen et al. 2017). In the case of developing countries, where the infrastructure gap is particularly pronounced, infrastructure investments are fundamental so that these countries achieve sustainable and inclusive growth and attain the Sustainable Development Goals (SDGs) (African Development Bank Group 2018).

According to the New Climate Economy Report, US\$94 trillion are expected to be invested in the period 2015-2030 across cities, land use and energy systems (New Climate Economy 2016). Two thirds of this amount will be directed to emerging economies and developing countries. On the other hand, the existing building stock will require extensive renovation and upgrading to improve the building thermal performance. The International Energy Agency has published a roadmap to sustainable buildings and has estimated the additional investments per continent required to lower the carbon footprint of the building stock and comply with the 2°C target (International Energy Agency 2013).

On a resource level, there are few studies that estimate the demand in resources under different scenarios. Especially with respect to non-metallic construction minerals, the available literature is scarce and data on their consumption have high uncertainty, although non-metallic construction minerals constitute half of the total material use (OECD 2018a; UNEP 2016). Some studies have drawn their conclusions about future issues in resource use based on the historic evolution of consumption patterns and have indicated the significant growth rate in per-capita income and material consumption, especially in developing countries, which drives the non-metallic minerals demand (Schandl et al. 2018; Schaffartzik et al. 2014). Schandl et al. (2018) also highlighted the need for material efficiency in the path toward the SDGs and indicated the importance of policy in ensuring resource efficient investments. Miatto et al. (2017) published a seminal study on the analytical calculation of global non-metallic mineral flows for the period 1970-2010, setting the basis for improving the accounts for these materials and for making more accurate future estimations. In the field of prospective assessments, Hashimoto et al. (2007) used material flow analysis to study the stocks and flows of construction minerals in the Japanese economy up to 2030 based on estimated construction and demolition rates. Wiedenhofer et al. (2015) modeled the material stocks and flows for the residential and transportation sector in the European Union in a business-as-usual scenario and highlighted the need for increase in resource efficiency in the industrialized countries with longer lifetimes and improved maintenance. Krausmann et al. (2018) calculated the evolution of the demand for construction minerals at a global scale and pointed out that sand, gravel and rock will be the resources with the highest volume of extraction in 2050. This observation is also underlined in the report of the Organization for Economic Co-operation and Development (OECD 2018a). Among the different construction minerals, here we focus on natural sand because of its significance for construction, the lack of systematic research around this resource in the existing literature and the current supply

shortage in construction sand that is already observed in some countries (Torres et al. 2017; Peduzzi 2014). Sand is one of the main components of concrete, the other components being Portland cement or another cementitious material, gravel and water. Sand is therefore essential for the economic and social development of countries (Ioannidou et al. 2017; Blengini et al. 2012) and has recently drawn the attention of the research community and the wider public. By the term sand, we here refer to natural sand and we exclude the dust from fracture or manufactured sand. Sand refers to a loose, non-cohesive granular material with particles between 0.05 and 2mm in size (Pettijohn et al. 1972). Natural sands vary in composition and chemical characteristics depending on the local rock sources (Hasdemir et al. 2016); very often they result from granite decomposition. Depending on the chemical composition of sand, its applications vary from construction to glassmaking, foundry and fracturing. Sand used in concrete is sand free from chlorides. Chlorides influence the rust layers on ferrous metal surfaces and therefore accelerate the corrosion of steel in reinforced concrete (Song et al., 2017). Sand is an abundant resource on a global scale, yet not all types of sand can be used for all applications; there are constraints in the sand extracted for construction. The particles of desert sand are too fine grained while marine sand has to be adequately desalinated to reduce the chloride levels for use in concrete. The sand cycle is far from equilibrium; sand is consumed in a much faster pace than it is generated. The extraction of large amounts of sand from rivers, lakes and the coast has a detrimental impact on the environment and biodiversity and the provisioning of ecosystem services (de Leeuw et al. 2010), leading to phenomena such as shoreline erosion (Gavriletea 2017; Torres et al. 2017; Anthony et al. 2015). Especially the loose governance framework and absence of control in some developing countries can lead to overexploitation of the sand resources and illegal mining. This can cause damage to the landscape and loss of an important resource (Gavriletea 2017). As a result, sand scarcity is becoming an emerging issue in industrial

ecology (Sutherland et al. 2017; Ioannidou et al. 2015). Different methodologies, such as System Dynamics and Game Theory, have been applied to evaluate the global sand resources considering current consumption rates and the involvement of the different parties in regulating sand extraction activities (Sverdrup et al. 2017; Podimata and Yannopoulos 2016). Sverdrup et al. (2017) evaluate the global sand resources, however in that study there is no differentiation in the required quantities at a country level.

In the current research, we evaluate sand through the prism of sustainable development; does the path toward the achievement of the SDGs create challenges in regional supply security of sand? Our study aims to identify potential hurdles for the infrastructure investments necessary for achieving SDGs from the angle of sand supply-demand balance. To this end, we estimated the sand requirements in different regions under different future scenarios of economic development, based on the Shared Socioeconomic Pathways and we compared future demand to the current extraction rate of each country (Crespo Cuaresma 2017).

<heading level 1> Methods and Materials

To estimate the expected construction sand demand under different future scenarios and compare it with the current levels of sand extraction per country, we translated the estimated construction investments to sand requirements based on the sand intensity of the construction sector in every country and accounting for the economic development trajectories delineated in the Shared Socioeconomic Pathways (SSPs) (Crespo Cuaresma 2017).

The SSPs is a set of five scenarios developed to represent different combinations of challenges to mitigation and adaptation with respect to

future climate, societal and environmental change (O'Neill et al. 2017). These scenarios account for possible changes in demographic, economic, social, technological, governance and environmental factors and through integrated assessment models estimate the future climate change impacts (O'Neill et al. 2017). In our study, we focused only on three of these scenarios. SSP1 (the Sustainability scenario) refers to a future with significant investments in environmental technology, rapid decline in inequality inside and among countries and improved resource efficiency (Riahi et al. 2017; O'Neill et al. 2017). SSP2 is consistent with historical patterns of growth, with consumption oriented towards material growth. There is a moderate environmental awareness and technological developments are not as important as in SSP1 (O'Neill et al. 2017). Finally, SSP3 represents a world of persistent regional inequality with slow development of low-income countries. This scenario postulates slow technological change, material intensive consumption with growing resource intensity and fossil fuel dependency. There is a low priority in the environmental policies and a pronounced nationalism, leading countries to focus mainly on domestic issues.

Below are the detailed steps we followed in our methodology.

Calculation of historic construction sand consumption. Since there are no direct data on the construction sand consumption per country, sand consumption was calculated indirectly based on data on the cement and bitumen consumption for the years 2000-2010. We estimated the amount of sand required in relationship to cement and bitumen in concrete production (Wernet et al., 2016) and asphalt design (Zapata and Gambatese 2005; Ahlrich 1991), respectively (eq. 1).

$$y_{j,sand} = 2.74 * y_{j,cement} + 3.8 * y_{j,bitumen} \quad (1)$$

Where y_j is the estimated consumption of sand, cement, or bitumen for country j .

The bitumen consumption per country is provided by the United Nations Statistics Division (2019). The cement consumption per country was calculated from data on the domestic cement production in this country extracted from the United States Geological Survey (USGS 2018) and data on cement imports and exports from the United Nations Commodity Trade (UN Comtrade) Statistics Database (United Nations 2017). The use of this database requires some caution, because there is often a discrepancy between the amounts reported by a country and its trade partners, due to different accounting practices and confidentiality issues (Gemechu et al. 2016). Trade statistics from European countries are usually complete while data from African countries or small islands are very often insufficient (Dittrich and Bringezu 2010). To address this uncertainty, we reconciled the amounts by accounting for average values: for every transaction between country X and country Y, we considered the average value of the amount reported by country X as import and by country Y as export. If for example country X reports that it imports 500 metric tons of construction sand from country Y in 2009 and country Y reports the amount for this transaction as 400 metric tons, we consider that the trade flow was 450 metric tons. Specifically for 54 countries that did not report any construction sand imports during the studied period 2000-2010, we did not calculate the average values but considered as accurate the amounts reported by their trade partners. Obviously, this assumption may underestimate the trade flows in these countries, since some amounts for reasons of confidentiality remain unreported. Detailed information on the calculation procedure is included in the Supplementary Information.

Calculation of sand intensity of construction. The sand intensity of construction expresses the amount of sand (in kg) required per US dollar (USD) of construction output and is a metric of the resource efficiency of the construction sector. In general, developing countries present a growth in the

construction sand intensity over the years. The process of industrialization and urbanization in these countries results in the use of modern materials (concrete and steel) to substitute traditional bio-based building materials (Miatto et al. 2017). As the economy of a country matures and there is a transition to a more industrialized construction, the material losses during construction are reduced and resource efficiency increases.

To calculate the sand intensity of construction, we extracted the construction output per country for the years 2000-2010 from two multi-regional Input-Output tables including the World Input Output Database (Timmer et al. 2015), and the OECD Input Output Tables (OECD 2018b), and from the UN data (United Nations Statistics Division 2019). Construction output data were available only for 129 countries. The construction output values were then adjusted to account for purchasing power parity and inflation (2010 levels). The countries were grouped based on their region and their level of income. We followed the classification of countries into Low income (class 1), Middle income (class 2), and High income (Class 3), according to the World Bank (2018). The sand intensity of the construction sector was calculated from the ratio of sand consumption over construction output. For the change in sand intensity, for each group of countries we considered two values as maximum and minimum respectively: a) the median value of the rates of change between 2000 and 2007 for all countries in an income group and b) the 25th percentile value. This range of values addresses the uncertainty in providing deterministic estimations for the evolution of the sand demand. In other words, in the worst case scenario, countries will continue the median historic trend, while in the best case, the countries in each group follow the example of the top performers.

Calculation of sand intensity for buildings and infrastructure. At this step, construction was distinguished into two categories: buildings and infrastructure. Infrastructure can include municipal infrastructure (such as roads, bridges), utilities, transportation (highways, rail, airports, and ports),

and social infrastructure, such as schools and hospitals (Sanwal and Zheng 2018). Detailed data from Input-Output Tables and from the country fact sheets of the European Construction Sector Observatory provided historic information for 36 middle and high-income countries about the construction output going to buildings versus infrastructure (IDE-JETRO 2005; European Commission 2019; Australian Bureau of Statistics 2015). A general assumption of 80%-20% allocation between buildings and infrastructure of the construction sand flows was adopted, based on Wiedenhofer et al. (2015). In literature, there are contradictory data regarding these allocation percentages. Hashimoto et al. (2007) estimated 75% of the sand quantity going to infrastructure versus 25% to buildings. Nevertheless, we adopted the values of Wiedenhofer et al. (2015) which are closer to the values reported by the industry and depict the net flow of aggregates, i.e. excluding the recycled aggregates. For the aforementioned 36 countries where data were available, we calculated the sand intensity of infrastructure $intensity_{j,i}$ and of buildings $intensity_{j,b}$ for every country j as the ratio of the quantity of physical sand flow over construction output in economic terms for the two sectors. Furthermore, for these countries, we calculated the ratio $intensity_{j,i}/intensity_{j,b}$ and the fraction of construction investment directed to infrastructure and we took the average values for middle and high-income countries. We assumed that the above ratios can be considered as approximately constant for all countries inside every income class. In addition, based on the sand intensity of construction from the previous step, which is a weighted average of the sand intensity of infrastructure and buildings, we were able to estimate the sand intensity of infrastructure and buildings for every country.

More detailed information on the calculations is included in the Supplementary Information.

Estimation of the sand requirements per country for the period 2015-2030.

The calculations were based on the forecasted construction investments and the sand intensities of infrastructure and buildings in every country. Three scenarios were tested, in alignment with the Shared Socioeconomic Pathway Scenarios SSP1, SSP2 and SSP3. These general scenarios were translated into construction growth and investment scenarios. The construction investments in infrastructure for the SSP1 scenario were matched to the predictions of the New Economy Report regarding the investment in infrastructure required for sustainable development (New Climate Economy 2016). The predicted investments depend on the level of development of every country; US\$94 trillion are expected to be invested in the period 2015-2030, and from this amount two thirds will go to developing countries (low and middle-income countries). This amount is further allocated to the countries inside each income class in proportion to their GDP. For SSP2, an extrapolation of historic trends was applied. For SSP3, we assumed a similar trend as in SSP2, only with lower GDP growth especially for the low-income countries. This slower economic growth decreased also the construction output. The GDP growth for all three scenarios was based on the forecasts of Crespo Cuaresma (2017) and for the change in sand intensity two values were considered, based on the second step of the methodology.

Regarding the construction investments in buildings, we used the report of the International Energy Agency (2013) as a data source. IEA estimates the investments in different world regions for the period 2010-2050 according to 2 scenarios: 6 Degree Celsius Scenario (6DS) which is a baseline scenario, largely an extension of the current trends while 2 Degree Celsius Scenario (2DS) is a scenario compliant with the goal of capping the global mean temperature rise relative to the pre-industrial era within 2°C. In the latter scenario, large-scale refurbishment in residential buildings is required to reduce the energy demand. In our model, the scenario SSP2 was an extrapolation of current trends, while SSP1 considered the difference in the

investments between 2DS and 6DS. SSP3 resembles SSP2, with different growth rates of the economy, especially for the low-income countries (class 1). All other explanatory factors in our scenarios besides construction investment (translated into sand intensity), sand intensity growth and GDP growth were assumed to remain the same.

Comparison of the per country sand requirements in 2030 to the current extraction levels of that country. Current sand extraction for every country was calculated by adding the net sand exports (difference between exports and imports) to the domestic sand consumption and taking the average for the years 2009 and 2010. The ratio of future demand (D_j) to current extraction (DE_j) per country j was calculated from the values of the previous step and the extraction amounts calculated here.

Validation of the model output using historical data. To validate the model, we tested its performance in predicting the sand consumption based on the construction output for 28 countries for the year 2014, namely countries of the European Union, Singapore and Brazil. These countries were selected because detailed data on investments directed to buildings and to infrastructure were readily available. No country in income class 1 was included due to lack of data. Figure 1 shows the sand demand estimated by the model versus the actual sand consumption, calculated based on the cement and bitumen consumption. We observe that the model can approximate quite well the actual consumption for most countries. The trendline and the high coefficient of determination ($R^2 = 0.97$) show a linear correlation of the estimated to the real data points. However, the trendline in Figure 1 does not cross the axes' origin; the real error in the calculation is higher. The average error between actual values and values yielded by the model is 44%. This error is largely due to the significant discrepancy in the values (error greater than 100%) for the countries of the European South

(Greece, Spain, Portugal) and Ireland. The economic recession that affected these countries impacted the construction sector and resulted in a negative resource intensity effect. Roinioti and Koroneos (2017) observed a similar negative energy intensity effect, due to the transition to more efficient energy-using technologies.

Figure 1. Sand demand estimated by the model versus actual sand consumption, calculated based on the cement and bitumen consumption

<heading level 1> Results

Figure 2 shows the annual global sand requirements for the years 2015-2030 under the three SSP scenarios. All three scenarios assume a sand consumption based on historical trends until 2015 and from 2016 on, the different assumptions apply, hence the steep step for SSP1 in the beginning of 2016 due to the additional investments in buildings and infrastructure. The figure also shows the range of possible values for the three scenarios,

depending on the rate of change of sand intensity. If the rate of change of sand intensity is close to the median value of each income group, then the scenario of a sustainable future (SSP1) requires more sand resources than the other scenarios. If we compare the upper value of cumulative global sand demand estimated in our model for the SSP1 scenario to the historic sand consumption of the last 40 years (1970-2010) (Miatto et al. 2017), we observe that the quantity that will be required in 16 years (2015-2030) is estimated around 500 billion metric tons and is more than twice the amount consumed in 40 years. The additional investments in buildings and infrastructure in scenario SSP1 have to be combined with a higher decrease in sand intensity, following the trend in the top 25% of countries in every group. The difference between scenarios SSP2 and SSP3 is small because of the adopted assumptions. Both are consistent with historic trends, with SSP3 assuming additionally that low income countries will lag in development, therefore the gap between high and low-income countries will increase. At the same time, in SSP3, middle income countries will continue their development path at a slightly lower rate. According to Crespo Cuaresma (2017), the growth rate for the middle-income countries in scenarios SSP2 and SSP3 is approximately the same. As the global consumption is largely defined by the consumption in the middle-income countries, which is dependent on the economic growth, therefore the cumulative global demand does not differ significantly in scenarios SSP2 and SSP3.

The observations from Figure 2 are in alignment with previous studies on major metals (e.g. aluminum, nickel, copper) (Schipper et al. 2018; Van der Voet et al. 2018). One of the findings in the aforementioned studies is that the abiotic resource depletion grew faster in the Equity/First/Sustainability scenario because GDP growth seems to drive resource demand. This finding is also validated in our study, where the sustainability scenario requires more sand, because of the increased investments in infrastructure and buildings.

Figure 2. Annual global sand demand for the years 2015-2030 under the three SSP scenarios

If we look at the estimated sand demand per country and per world region, we note that China will require considerable amounts of construction sand (Figure 3). In general, developing countries and emerging economies will require the majority of the total amount of sand consumed globally in the period 2015-2030. If we break down the sand demand to buildings and infrastructure, the infrastructure has a higher contribution to the total amount of sand required (see Supplementary Information). On the other hand, the investments in infrastructure are significantly lower than the investments directed to buildings. This observation shows the significant impact of the sand intensity in infrastructure construction.

To satisfy the increased future requirements, especially under SSP1 scenario, a lot of developing countries will need to extract multiple times the amount of sand they are currently extracting (Figure 4). The maps show the large disparity across countries; developed economies have a quite stable sand demand whereas a significant supply-demand gap is particularly observed in South-East Asia and Africa. The massive growth in resource consumption in

these countries is related to their transition from an agrarian, biomass-based economy to an industrial, mineral based, urbanized economy (Schandl and West 2010). This transition is linked to increased material use, reaching rates much higher than the economic growth of the country (Humphreys 2018). As the economy of a country matures, development is oriented toward service sector activities, leading to a decrease in material intensity. The grey color of many countries in Figure 4, especially in Africa, is due to missing economic data that did not allow any estimation of the future sand demand.

Figure 3. Estimated sand demand (in million metric tons) per world region for the year 2030 according to SSP1, SSP2 and SSP3. The bar “Extraction” in all the graphs represents the average annual amount of sand extracted currently in every region (based on data for the years 2009 and 2010). The bars SSP1, SSP2, SSP3 show the amount of sand required in 2030 if the rate of change in sand intensity is equal to the 25th percentile of each income

group. The error bars show the estimated amount if the change in sand intensity is equal to the median of each income group.

(a)

(b)

(c)

D/DE

Figure 4. Future demand (D_j) to current domestic extraction (DE_j) ratio for countries where data was available under the scenarios SSP1 (map a), SSP2 (map b), SSP3 (map c). The estimations are based on the maximum rate of change in sand intensity

<heading level 1> Discussion

The critical role of sand in construction has been the reason that fast-growing economies such as Singapore and Dubai in the United Arab Emirates face excessive domestic sand demand that cannot be satisfied at a local level (Peduzzi 2014; Torres et al. 2017). These economies resort to importing construction sand even from remote countries, such as Australia. Our analysis showed that if extraction rates remain similar to present ones, especially in developing countries, many areas will face the same challenges in view of the anticipated increased sand requirements.

In this case, the question is whether such an increase in the extraction rates is feasible in an environmentally sustainable manner. For example, the region of South-East Asia has already been heavily exploited by providing sand for the infrastructure development of Singapore. Figure 5 shows the large volume of construction sand imported by Singapore from Vietnam, Cambodia, Myanmar and the Philippines between 2009 and 2010. Illegal sand dredging in this region, despite official bans in sand exports to Singapore, had an impact on the aquatic ecosystem (Global Witness 2010). Therefore, sustainable development and the achievement of the SDGs by continuing current practices may hinge upon availability of natural resources. More specifically, the extraction of construction sand can directly impact the SDGs 9, 11 and 12 related to construction, urbanization and resource consumption and indirectly the SDGs 13, 14 and 15 related to the protection of the environment. Extracting sand without destroying the environment and negatively affecting rivers and lakes is a challenge that

researchers and policy makers are called to solve. Further research should investigate, for example, whether countries in South-East Asia can satisfy their demand locally without irreparably impacting their environment.

Figure 5. Main countries importing and exporting construction sand in 2009-2010 (average of the two years). The flows connecting different arches of the circle are directed from the exporting country (start point in the external arch) to the importing country (internal arch). ISO codes are used for the countries: SGP: Singapore, VNM: Vietnam, PHL: Philippines, KHM: Cambodia, MMR: Myanmar, MYS: Malaysia, CAN: Canada, BEL: Belgium, NLD: Netherlands, DEU: Germany, CHE: Switzerland, FRA: France, GBR: Great

Britain, ESP: Spain, LUX: Luxembourg, CHN: China, HKG: Hong Kong. The amounts are in million metric tons.

The issue of local scarcity and management of sand is similar to the water scarcity problem. Both are locally scarce and overexploited natural resources (Ridoutt and Pfister 2010). Shortage in the local freshwater supply leads to price increases (Olmstead and Stavins 2009), which make the use of various treatment processes such as desalination economically feasible. Similarly, the use of marine aggregates and their treatment to remove the chlorides is a more expensive solution which may however be justified when there is no easily accessible sand. In addition, local scarcity has led to a commodification of water and to the emergence of the concept of virtual water flows. Likewise, sand is becoming a commodity; in the case of local supply shortage, demand is satisfied through trade even over long distances. Figure 5 shows the main countries importing and exporting construction sand in 2009-2010. The flows connecting different arches of the circle are directed from the exporting country (start point in the external arch) to the importing country (internal arch). The biggest sand exporters are Singapore and Belgium. Singapore is only an importing country while Belgium also exports construction sand, mainly to France. In the figure, we can observe the significant trade of sand, usually between neighboring countries but in some cases over long distances (Singapore importing from the Philippines, Belgium from China). This sand trade presents similar characteristics to the virtual water flows in that the resource deficit becomes invisible by importing commodities which are available at a low production/extraction cost (Allan 2003). Nevertheless, the trade of a bulky material, like sand, may be prohibitive in the future for some countries depending on the availability of long range transport, the ability of the countries to pay for this commodity and on social factors (Sverdrup et al. 2017). Furthermore, Switzerland and Luxembourg, despite their small size, are importing significant amounts of

construction sand, according to the figure. This poses the question to what degree small countries can be resource sufficient.

In addition to trade, the use of substitutes can also offer a solution to the issue of sand scarcity. In the existing literature, there are many studies that assess the potential of different types of slag from the production and refining of various metals to substitute sand in concrete. Possible such substitutes are steel slag (Saputro 2018), slag from the refining of lead and zinc (Tripathi and Chaudhary 2016) and rapid cooling electric arc furnace oxidizing slag (Kim et al. 2016). Other industrial wastes, such as palm oil clinker, coal bottom ash (Ong et al. 2018), fly ash (Rafieizonooz et al. 2017), fixated phosphate industry waste (Lieberman et al. 2018) and waste from granite and marble processing (Singh et al. 2016) can also be used to partially replace sand. Li and Yang (2017) examined how to use demolition waste of old concrete as fine aggregates. Finally, materials at the end of their lifecycle, like spent fluorescent lamp glass (Ling and Poon 2017) and waste plastic (Thorneycroft et al. 2018) can prove possible alternatives of sand. However, the use of the aforementioned substitutes is quite limited, especially in a conservative sector such as construction, where the integration of innovative materials usually has to be underpinned by the relevant policies. Marine aggregates can be another, more expensive solution for use in construction. The dredging of offshore sand requires specialized equipment and special environmental permits. Nevertheless, sea aggregates contain chlorides and require treatment for elimination of the salt content to avoid steel corrosion in reinforced concrete (Liu et al. 2017). Use of not properly treated sea sand can have detrimental consequences on the structure of a building (Marshall et al. 2011), increasing the risk of structural failure even under static loads (Çağatay 2005).

Further research should be directed both to the use of alternative substitutes in concrete as well as to the processing of not-suitable forms of sand for use in construction. For example, Neumann and Curbach (2018) research the possibility of thermal treatment of desert sand, an energy and cost

demanding process that could however provide a solution if the price of sand increases. Moreover, investments are required for exploration of sand deposits and for identifying zones of extraction of marine aggregates. Local sand shortage should also give rise to adaptive infrastructure development; investments should be directed to the use of locally abundant resources, such as earth and bamboo. Earth construction is part of the vernacular architecture of many African countries (Dalibi 2017). It presents the advantage that the resource does not need to be transported over long distances, is less energy-intensive, with infinite recycling possibilities and with minimal waste in the construction process (Pacheco-Torgal and Jalali 2012; Ouellet-Plamondon and Habert 2016). This resource can be used on a large scale in construction in the form of self-compacting clay concrete, which is fast, cheap and can be scaled up to address the urbanization challenge (Landrou et al. 2016). On the other hand, bamboo is a renewable, bio-based resource growing naturally in Africa, Asia, America and Oceania and is part of the traditional construction in many countries of southeast Asia and Latin America (Zea Escamilla et al. 2018). These construction materials cannot fully replace but can significantly reduce the use of reinforced concrete in the developing countries. Additional benefits such as employment of local workforce and reinforcement of the local economy should also be considered in the selection of the resources for the development of the economies of the global South (Ioannidou et al. 2018). Along these lines, Rennkamp and Boyd (2015) advocate that a technology transfer in the developing countries should be oriented toward underpinning the local manufacturing capacities.

Limitations. The current study has not accounted for the different types of construction sand (e.g. river sand versus dune sand), their properties and particle size distribution which can influence the workability and compressive strength of sand-concrete mixes. Therefore, specific uses may require the use of specific types of sand. In addition, silica sand and its industrial applications were out of the scope of the current study. Another limitation of

the research is related to the missing data about many developing countries. As a result, our calculations and the values presented in this paper excluded the sand consumption in these areas. Global sand demand in the future scenarios would be higher if the missing data were also considered. However, this will not change the observations and main conclusions of the study. Finally, there is inherent uncertainty in the shared socioeconomic pathway scenarios used to estimate the future trends. These scenarios are an attempt to investigate different futures and what would be the ensuing impact on sand demand under the specific assumptions. Their value is that they can highlight potential issues and can allow us to address them proactively through policy and other economic measures and do not necessarily represent the actual future condition. For example, the economic recession which was observed in Figure 1 has not been considered in the assessed scenarios. In the case of such a recession, investments in the construction sector, and commensurately the demand for sand, are significantly reduced.

<heading level 1> Conclusion

The path to sustainable development and low-carbon future requires significant investments in infrastructure and buildings, both in new construction and in the maintenance, renovation and upgrading of the existing one. Especially developing countries will need to invest in new infrastructure, such as roads, hospitals, transportation, in order to achieve the Sustainable Development Goals. Our study examined the implications of low-carbon and sustainable infrastructure development on regional sand demand and supply. Our point of departure was the forecasts by the New Economy Report and the International Energy Agency report on the expected construction investments in infrastructure and buildings until 2030. These forecasts were juxtaposed to economic development scenarios based on

Shared Socio-economic Pathways (SSPs). The model was based on data from the years 2000-2010 and was validated for 28 countries using the data for 2014.

The results showed that our ability to realize low-carbon, sustainable infrastructure envisioned by the New Economy Report may hinge upon the availability of sand resources, unless the sand extraction rates or the current construction practices change radically. Among others, the development scenario (SSP1) requires more construction resources if sand intensity in construction follows historic trends. In particular, developing countries in South East Asia and Africa are expected to require sand at multiple times their current extraction rates. Under these conditions, sand may become a future currency for infrastructure development. Therefore, alternative and innovative solutions are needed for the sustainable growth of the global South to mitigate greenhouse gases and to meet the SDGs. Our results indicate the needs to investigate alternative pathways to infrastructure development especially for the low-income and emerging economies, which shall consider not only modern concrete construction but also local materials and local workmanship.

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