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Carbon Emissions of Infrastructure Development

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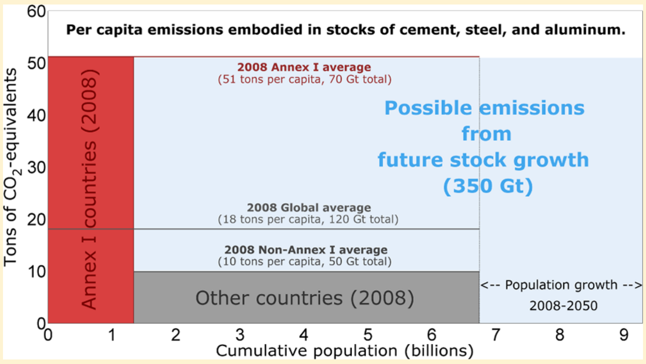
S *Supporting Information*

ABSTRACT: Identifying strategies for reconciling human development and climate change mitigation requires an adequate understanding of how infrastructures contribute to well-being and greenhouse gas emissions. While direct emissions from infrastructure use are well-known, information about indirect emissions from their construction is highly fragmented. Here, we estimated the carbon footprint of the existing global infrastructure stock in 2008, assuming current technologies, to be 122 (−20/+15) Gt CO_2. The average per-capita carbon footprint of infrastructures in industrialized countries (53 (±6) t CO_2) was approximately 5 times larger that that of developing countries (10 (±1) t CO_2). A globalization of Western infrastructure stocks using current technologies would cause approximately 350 Gt CO_2 from materials production, which corresponds to about 35−60% of the remaining carbon budget available until 2050 if the average temperature increase is to be limited to 2 °C, and could thus compromise the 2 °C target. A promising but poorly explored mitigation option is to build new settlements using less emissions-intensive materials, for example by urban design; however, this strategy is constrained by a lack of bottom-up data on material stocks in infrastructures. Infrastructure development must be considered in post-Kyoto climate change agreements if developing countries are to participate on a fair basis.



1. INTRODUCTION: THE NEXUS OF HUMAN DEVELOPMENT AND CLIMATE CHANGE

Infrastructures, which represent the entirety of built environment stocks in this study, lie at the nexus between human development and climate change. Infrastructures are critical for satisfying human needs for food, water, energy, sanitation, shelter, transportation, and communication, and their development is therefore essential for alleviating poverty and promoting economic growth.[1,2] Infrastructures also cause anthropogenic greenhouse gas emissions throughout the entire socio-metabolic system (Figure 1). These emissions first occur during the construction phase (emissions in materials production, manufacturing, and construction, including energy industries), then in the use phase (e.g., transportation or buildings), and finally, to a lesser extent, they occur in the end-of-life phase (waste management). Due to their long service lifetimes, infrastructures determine to a large extent how the carbon emissions of a society change over time.[3] While direct emissions from the use phase are produced simultaneously with service delivery, indirect emissions from the production phase are often generated decades prior to service delivery. Infrastructure development thus shapes essential boundary conditions for development and emissions abatement over long time periods in all major sectors.

The long infrastructure lifetime severely affects the drastic, timely reduction of greenhouse gas emissions that will be necessary to limit the average global temperature rise to 2 °C compared to preindustrial levels, which is the guard rail adopted in U.N. climate negotiations to prevent dangerous anthropogenic interferences with the climate system. In 2008, the total fossil fuel-related CO_2 emissions, which constituted approximately 57% of the total greenhouse gas emissions,[4] accounted for approximately 32 Gt in 2008.[5] The distribution of these emissions among the global population varies significantly by country (Figure 2A). On average, the per capita CO_2 emissions in industrialized (Annex I) countries were 10.2 t, while the global average was 4.1 t. According to the Intergovernmental Panel on Climate Change (IPCC), global emissions must be reduced by 50−85% between the years 2000 and 2050 to limit global warming to 2 °C.[4] Assuming that the global population reaches 9.3 billion in 2050 and that the relative contribution of fossil fuel based emissions is proportional to that of total greenhouse gas emissions, the average global per capita emission from fossil fuels needs to be reduced to 0.4−1.3 t/cap, indicated by the horizontal red bar in Figure 2A.

Such emissions cuts pose an unprecedented challenge for infrastructure development in industrialized and developing

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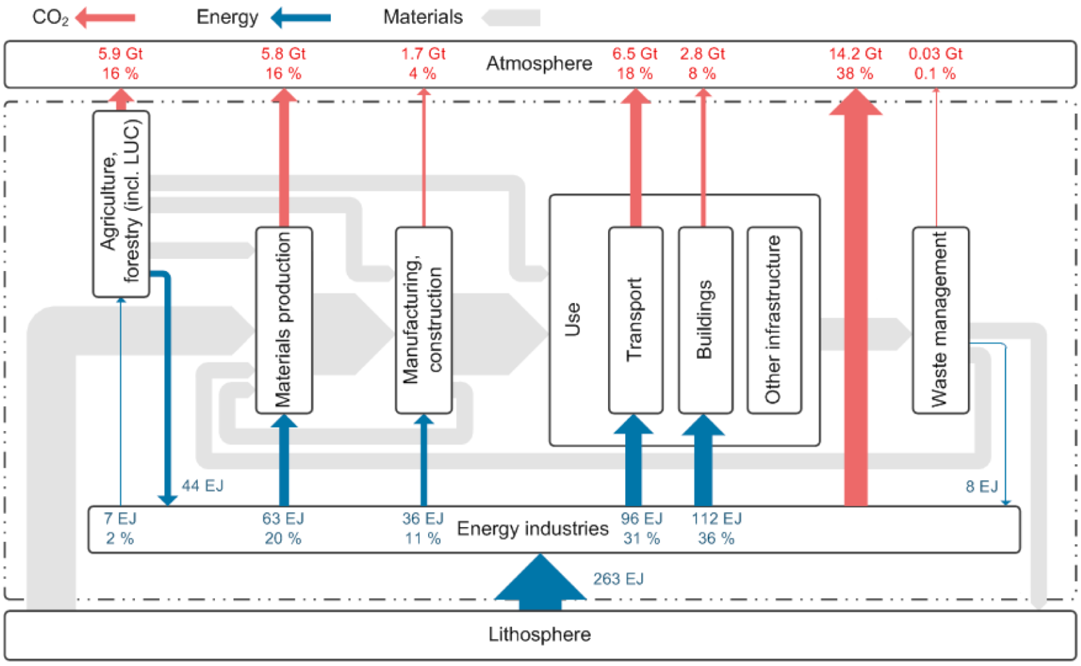

Figure 1. Global socio-metabolic system showing the links between the major sectors (boxes within the system boundary) and the environment (boxes outside the system boundary) through material (gray arrows), energy (blue arrows) and CO_2 emission flows (red arrows) in 2008; infrastructures play a central role for the socio-metabolic system due to their direct and indirect emissions; short-cycle emissions and assimilation from biomass and water were excluded. LUC: land use change. The CO_2 data were based on the Emissions Database for Global Atmospheric Research (EDGAR, version 4.2).[5] The energy data were compiled from the International Energy Agency (IEA).[36−38] See Supporting Information for more details.

countries. A fair amount of research has been dedicated to explore options for cutting direct energy use and emissions of individual infrastructure systems, such as buildings[6,7] automobiles,[8] and industrial sectors.[3,9,10] Models for aggregate infrastructure stocks, such as those produced by Davis et al. or Williams et al.,[11,12] consider infrastructure stocks as energy users and greenhouse gas emitters; however, these models do not include the materials necessary to build the infrastructures, and hence omit essential socio-metabolic linkages between infrastructures and the material producing sectors that necessary to understand the full implications of infrastructure development. Indirect or embodied emissions have been studied in carbon footprint analyses for individual products and on an aggregate level for final consumption within geographical areas and in international trade.[13−15] While these studies focus on emissions embodied in consumption and trade *flows*, there is a lack of studies that address emissions embodied in *stocks* of materials and products in use. This gap partly reflects the lack of aggregate data on infrastructure stocks and, more importantly, their material composition.

Understanding the emissions embodied in existing infrastructure stocks is fundamental in order to estimate future emissions from infrastructures to be built in developing countries and to identify effective strategies for reducing indirect emissions.

In this study, we analyzed the indirect, material-related emissions associated with the current infrastructure stocks in all major countries using a top-down approach for the key materials, and used the values of industrialized countries as a benchmark for future infrastructures in developing countries that render similar services. Due to their long service lifetime, aggregate infrastructure stocks usually consist of materials that were produced through a long period of time, during which technology (e.g., emissions per ton material) and resource use (e.g., primary versus secondary resources) changed. The allocation of a carbon footprint to stocks with a mixed age structure and changing production technologies is therefore not trivial. Indicators for the carbon footprint of stocks may be differentiated according to their allocation of time and production technology.

In accounting, the value of an asset can be expressed, among others, as the historical cost (original monetary value) or as the replacement cost (cost of replacing an asset with current prices). Similarly, the carbon footprint of a stock can be defined as the historical emissions produced to build up the stock, or as the carbon emissions that would be generated if the existing stock was replaced using current technologies. As emissions per ton of material produced tend to decline, the replacement value expressed in carbon (here called “carbon replacement value, CRV”) is generally smaller than the historical value expressed in carbon (here called “CHV”). In this study, we determine the CRV of stocks, because this value is better suited when using the stocks in industrialized countries as a benchmark for stocks in developing countries.

For the technology assumptions, one may differentiate three approaches: (i) stocks produced from primary resources count as primary, stocks produced from secondary resources count as secondary; (ii) all stocks, independent of whether they were ultimately produced from primary or secondary resources, count as primary; (iii) stocks produced from primary resources count as primary, stocks produced from secondary resources count as primary plus secondary (or several secondary productions, dependent on the number of cycles the material has undergone prior to its current use). The first approach considers only the last production cycle of the material stock, while the responsibilities for the historical emissions from

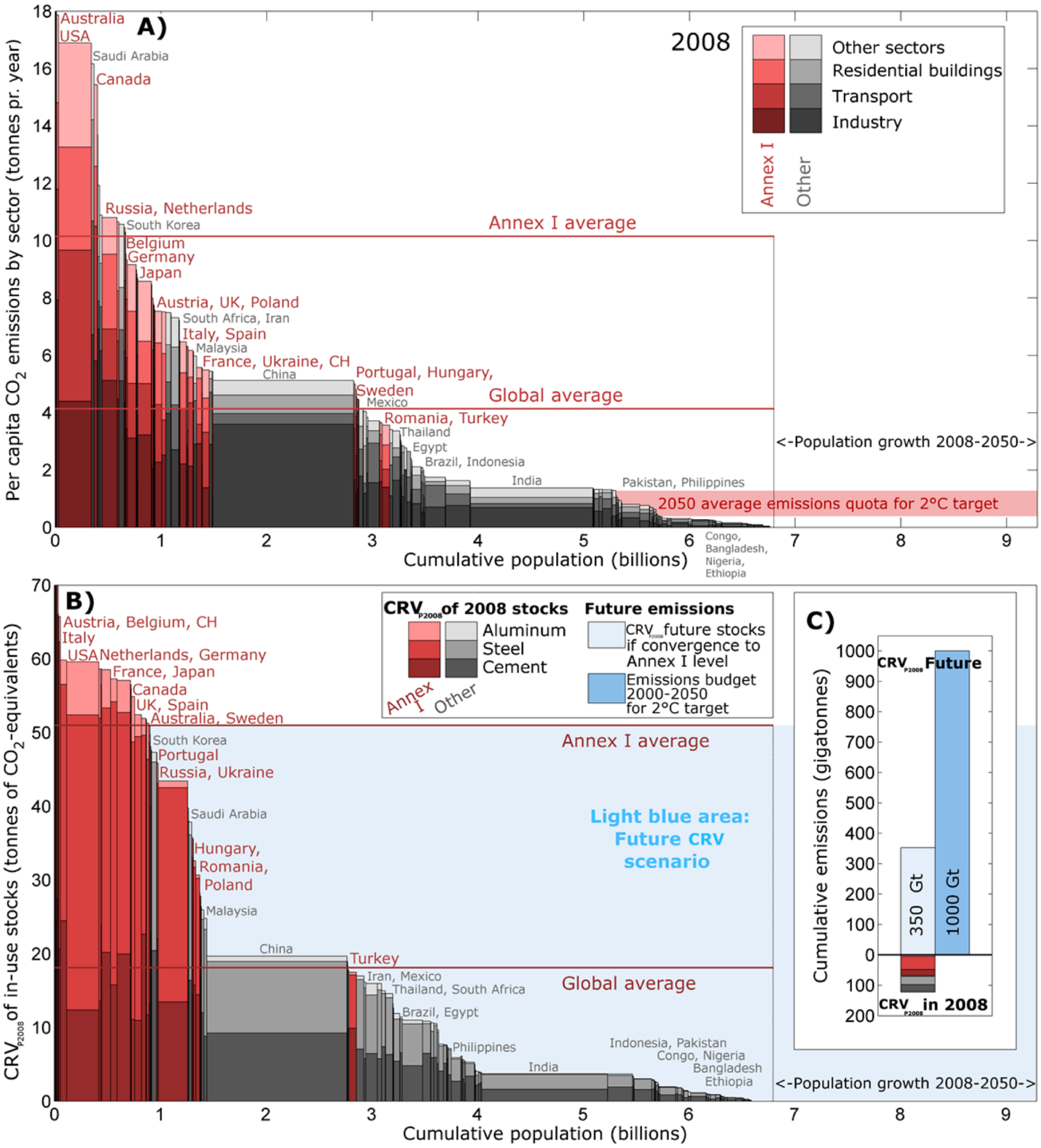

Figure 2. (A) Total fuel-related per-capita CO_2 emissions by country (red and gray bars) compared to the global per-capita emission level in 2050 to reach the 2 °C target with a 50−75% probability (red horizontal bar); (B) CRV_{P2008} per capita of existing stocks by country (red and gray) and of as-yet unbuilt stocks if developing countries converge on the current average Annex I level (light blue); (C) comparison with emission budget for the period 2000−2050 to reach the 2 °C target with a 75% probability. Of this emission budget (1000 Gt), approximately 420 Gt was already emitted during the period from 2000 to 2011.

primary production are canceled by the act of recycling. Using this approach as a benchmark, developing countries would not be able to build up stocks similar to those in industrialized countries because they do not dispose of sufficient obsolete infrastructures that could serve as a source of scrap and instead depend heavily on the use of emissions-intensive primary production. The second approach accounts for the fact that all service-providing materials were once produced using primary production, that stock growth can only be accomplished by primary production, and that therefore developing countries cannot build up their stocks based on recycling; however, it does not capture the replacement of a stock (recycling). The third approach accounts best for the entire production-related historical emissions, but it creates significant accounting challenges (for example, should obsolete stocks be included, and if yes, how can they be allocated to the current stocks in use?). If used as a benchmark, this approach would allow developing countries to build larger stocks than industrialized countries currently dispose of because their stocks tend to be younger and less recycled. Here, we employ the primary production approach since it allows for a benchmarking that is oriented toward achieving similar infrastructure levels, without rewarding or punishing the historical development of stocks.

We call the indicator CRV_P or CRV_{P2008} to indicate the selected reference year 2008. It reflects the expected greenhouse gas emissions released if the stock was replaced using current (about 2008) standard technologies based on primary production.

We aim to answer the following questions:

1. How large is the CRV_P of existing infrastructure stocks in different countries?

2. How large is the emissions budget (CRV_P) required by developing countries if they were to develop Western style infrastructure stocks (Contraction and Convergence)?
3. What options do developing countries have to reach infrastructure service levels of industrialized countries with a lower CRV_P (leapfrogging)?

2. MATERIALS AND METHODS

The CRV_P was determined for the year 2008 using the three key materials steel, cement, and aluminum as a proxy. In 2008, these materials accounted for nearly half of industrial emissions (25% steel, 19% cement, and 3% aluminum) and 17% of total energy- and process-related CO_2 emissions.[16] Emissions of other materials are either less significant for infrastructure stocks (e.g., plastic and paper, which together constitute about 3% energy- and process-related emissions) or contribute significantly smaller amounts of emissions (e.g., other metals, gravel). The CRV_P for each material was determined by multiplying the data for the material stocks by the corresponding emission coefficients for primary production. We calculated the stocks for steel,[17] cement (see Supporting Information (SI), SI-1), and aluminum[3] using a top-down approach based on country-specific historical data for production, international trade of the materials along the entire supply chains, and assumptions about the lifetime distribution of the main product categories (such as buildings and construction, transportation, machinery and equipment, and packaging). For system definition, model approaches, and data used see SI SI-1 and cited literature. Our estimates of the CRV_P are conservative due to the omission of other materials and manufacturing and construction. We determined the CRV_P for these key materials found in existing infrastructure stocks on a country-by-country level and used the average CRV_P in industrialized countries as a benchmark for the indirect emissions of future infrastructures in developing countries, by assuming that these countries will eventually reach service levels that are similar to those in industrialized countries.

Sensitivity analyses were conducted for all three materials and their corresponding CRV_P values. The largest uncertainties resulted from the assumptions on service lifetime distribution (the difference in the stock estimates for short- and long-lifetime assumption was approximately 30%[3,17]). Trade and material concentration data for individual products may come with high uncertainty; however, the aggregate uncertainty was relatively low due to the large number of trade flow categories considered (less than 10% for the trade data and approximately 20% for the material concentrations in the final products[3,17]).

Mitigation options for reducing primary production emissions in developing countries were divided into approaches for reducing the emission intensity of materials and approaches for reducing the material stock per service unit. The potentials for reducing the emission intensity of the materials were tested with steel and aluminum cycle model simulations, and different combinations of measures, that include the best available technologies and technologies currently under development for different processes, were employed.[3,9] No data were found for the aggregate material stocks of urban systems. Car ownership and the network length for water, wastewater, and road systems were therefore used as crude proxies for the material stocks of these subsystems. Urban density was selected as one of many factors potentially relevant for saving materials per service unit. The definitions and data sources are documented in the SI.

3. RESULTS AND DISCUSSION

We estimated that the existing global infrastructure embodies 122 (−20/+15) gigatonnes CO_2-eq (Gt CO_2; 1 Gt = 10^{12} kg), with 68 (−13/+10) Gt CO_2-eq in Annex I countries and 53 (±6) Gt CO_2-eq in non-Annex I countries (Figure 2b). The SI SI-2 contains a list of CRV_{P2008} per country for steel, cement, and aluminum. The average global citizen uses stocks of these three materials with a CRV_P of approximately 18 (−3/+2) t/cap. The CRV_P of the average Annex I citizen (51 (−10/+7) t/cap) is approximately five times larger than that of the average non-Annex I citizen (10 (±1) t/cap).

In comparison, the total global anthropogenic CO_2 emissions (excluding agriculture, forestry, and land use change) were approximately 30.9 Gt/year or 4.6 t/cap/year in 2008.[5] Thus, the current global material stock 'is worth' approximately 4 years of current total CO_2 emissions.

The per-capita CRV_P range among Annex I countries (Figure 2B) is small compared to the large differences in materials production and annual CO_2 emissions (Figure 2A). This could be interpreted in a way that currently no industrialized countries could serve as role model for developing countries in designing and constructing their settlements with significantly lower amounts of carbon-intensive materials (leapfrogging). However, the per-capita CRV_P values differ significantly between Annex I countries and the remainder of the world, indicating a serious emissions burden for developing countries.

We use the current average per-capita CRV_P of industrialized countries (51 t CO_2/cap) as a benchmark to estimate the emissions required in developing countries that are expected to expand their built environment stocks to the current level of industrialized countries. We further assume that industrialized countries will forego further stock expansion and that global population will grow to 9.3 billion by 2050.[18] In this scenario, the CRV_P of the global infrastructure would grow to approximately 470 Gt CO_2, where 75% of that Figure (350 Gt CO_2) still would have to be emitted from infrastructure-related primary materials production. Since most of the infrastructure development *and* most of the population growth is expected to take place in the developing world, these poorer countries need an emissions budget of close to 350 Gt CO_2 in a Contraction and Conversion scenario that assumes current technologies (production technology and infrastructure design).

In comparison, Meinshausen et al. demonstrate that in order to limit the average global temperature rise to 2 °C above preindustrial levels, the cumulative emissions during the 2000−2050 time period cannot exceed 1000−1440 Gt CO_2 (assuming 75% or 50% probability of reaching the target, respectively).[19] From 2000 to 2011, approximately 420 Gt of CO_2 were emitted due to human activities,[20] which leaves an emissions budget of approximately 600−1000 Gt CO_2 for the period from 2012 to 2050. Under the assumption of current technology, the emissions budget for infrastructure development in developing countries (350 Gt) would use up between 35% and 60% of the remaining budget available if the 2 °C guard rail is to be kept. In addition, Davis et al. estimated the cumulative emissions from existing infrastructures (including materials production) in the period 2010−2060 to be approximately 500 Gt CO_2.[11] Given the large amount of emissions that are not directly

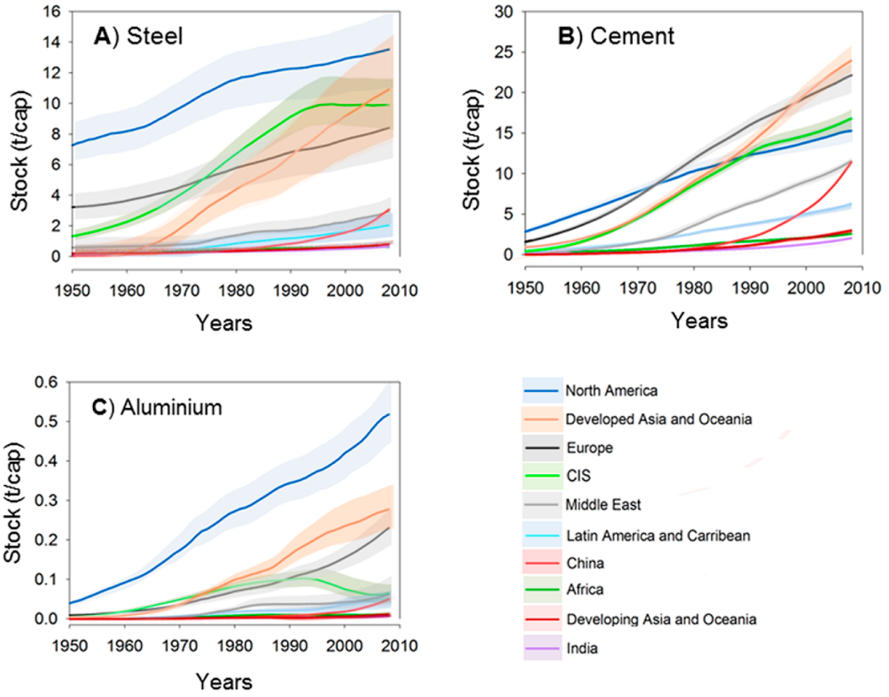

Figure 3. Historical per-capita stocks of steel (A), cement (B), and aluminum (C) by world region. The bands indicate the uncertainty ranges. Most material stocks are growing in all of the world's regions, although saturation has been found for several individual industrialized countries in the case of steel.[17,39,40]

related to materials (Figure 1), it is apparent that the up-scaling of Western-type infrastructure stocks to the global level may compromise the 2 °C target unless direct emissions of the newly built infrastructures are close to zero, which would be extremely difficult to achieve.[4]

The $\mathrm{CRV_P}$ as well as the derived benchmark of 51 t CO_2 per capita are conservative because it (i) it is assumed that stocks in industrialized countries are not growing further, for example due to infrastructure development for climate change adaptation, (ii) it is further assumed that no primary production is needed to maintain a certain level of in-use stock, implying that either the lifetime is indefinite or that all materials are recovered at the end-of life, and (iii) maintenance and replacement of existing infrastructures, which may be needed to reduce direct emissions, are not considered in the $\mathrm{CRV_P}$ indicator (see Figure 3). One may argue that it is unlikely that developing countries will have reached a Western level of infrastructure services by 2050. However, any infrastructure growth after 2050 would have to be accomplished with close to zero emissions in order to remain on track with the 2 °C guard rail. Given these limitations, the results do not provide realistic or expected emission estimates; rather, they represent a thought experiment to indicate the relevance of infrastructure stocks for reaching ambitious climate targets.

The results bring into question the method by which the 2 °C target could be reconciled with the principle of equity with respect to infrastructure services, if this is possible at all. The principal options for reducing the $\mathrm{CRV_P}$ of future infrastructures can be identified by employing a Kaya-like decomposition for the emissions F as follows (P stands for population, S for the service level of infrastructures, and M for the material stock):

$$F = P \times \frac{S}{P} \times \frac{M}{S} \times \frac{F}{M} \tag{1}$$

Assuming that the population (P) is given and the service level per capita (S/P) can be defined using industrialized countries as a reference, the $\mathrm{CRV_P}$ of future infrastructures can be reduced by the two following approaches: (i) reducing the emission intensity of the materials (F/M) and (ii) reducing the material stock per service unit (M/S).

Options for reducing the emission intensity of materials (i) include reducing energy use per ton of material, reducing process emissions, and lowering the carbon intensity of the energy supply. The potential of these measures has been analyzed in detail in various scenarios.[3,9,16,21] Because energy has been a major cost factor in previous years, the material producing industries tend to be very energy efficient already, which results in a limited remaining potential of energy efficiency improvement per ton of material of approximately 12% for aluminum, 13% for cement, and 24% for steel, while more substantial reductions often require carbon capture and storage (CCS) (see SI SI-1).[3,9,22] Similarly, process emissions from aluminum production have been reduced drastically over the recent decades, which leaves limited room for further reductions.[23] Partial substitution of clinker could reduce process emissions from cement production, but may be constrained by availability of blast furnace slag and fly ash.[24] In their most ambitious scenario the International Energy Agency assumes a reduction of the average clinker factor from 78% to 71% by 2050, which in combination with energy efficiency and alternative fuel measures would reduce emissions intensity from 0.80 to 0.56 kg CO_2/kg cement.[25] However, widespread use of less carbon-intensive energy is limited due to either large land commitments[22] or high costs.[26] Hence, the International Energy Agency predicts only a modest substitution of carbon-intensive energy sources by the year 2050.[21] Such a slow decarbonization of the energy system could entail that the window of opportunity to reduce emissions most effectively when the stock growth is largest cannot be

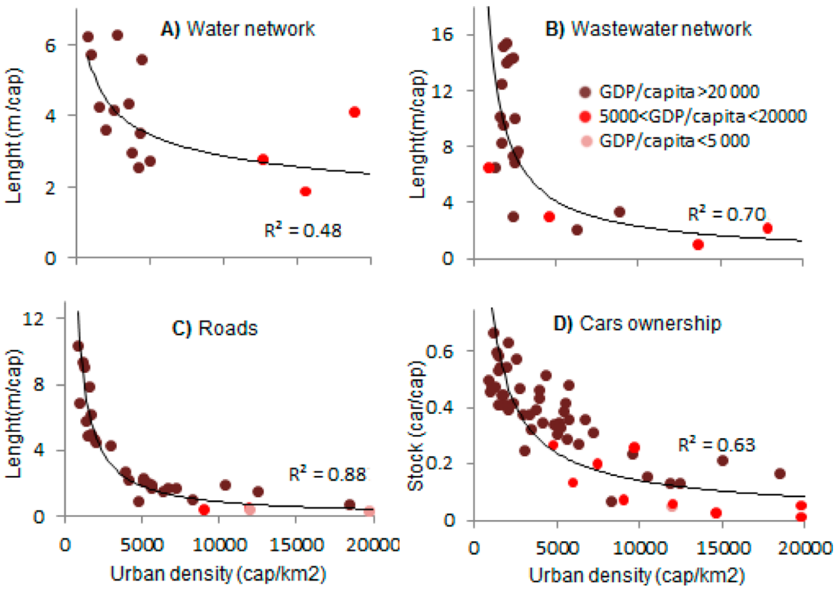

Figure 4. Impact of urban density and per-capita GDP (PPP, measured in current international dollars) based on network length and vehicle ownership: (A) water network, (B) wastewater network, (C) road network, (D) car ownership. Cities with higher densities tend to have lower per-capita network length and vehicle ownership, indicating potentially smaller per-capita stocks and related CRV_Ps.

sufficiently opened in the most critical phase of urbanization and industrialization.

The portfolio of emissions-reduction strategies designed to reach the 2 °C target may be broadened by strategies that decouple material use from services (ii). They can be divided into (iia) strategies for weight reduction on a product level and (iib) strategies for weight reduction on the level of urban systems. Studies of individual structures (iia), ranging from alternative metal forming processes to product design, suggest a large, yet underexplored potential. Examples include the light weighting of vehicles[22] or buildings. In the latter case low-rise medium-density homes in Australia were found to be less energy-intensive in construction than detached homes due to the savings in shared walls, economies of scale, and the surface area to volume ratio. For buildings taller than three stories, however, the embodied energy per floor area rises due to exponentially increasing structural material demands.[27,28]

On the urban or regional scale (IIb), however, savings on the product level can be reinforced or undermined by the urban form. Because the CRV_P values of infrastructures among industrialized countries were found to be fairly similar (Figure 2B), one could argue that the overall potential for decoupling is limited despite the large differences among individual urban and regional structures. In a carbon-constrained world, however, a deliberate design of settlement structures may yield a great potential to reduce infrastructure demand and subsequent demand for transporting goods and people. There exists some evidence that urban density, as one important parameter of measuring urban form, impacts the demand for infrastructure service. For example, studies on road networks[29] and urban water and wastewater networks[30] suggest that per capita network length and material stocks tend to decline with increasing urban density (Figure 4). Furthermore, more densely populated urban areas were found to provide incentives for modal shift from cars to public transport or cycling, and it was concluded that increasing density tends to lead to lower vehicle ownership[31,32] and direct emission, but also to lower material stocks and indirect emissions. However, more densely populated urban areas may limit the options for using emissions-saving construction materials for buildings, as the use of the latter is restricted to low-rise buildings.[27,28]

Design principles for cities that consider the different scaling effects for direct and indirect emissions of individual structures have not yet been developed. The development of such design principles is severely hindered by a lack of bottom-up data for materials used and stored in infrastructures. Greenhouse gas inventories that are based on a production approach[33,34] typically neglect both, materials used and materials stored within the territory of interest. Emissions inventories based on a consumption approach, for example,[35] account for all indirect emissions from materials (for example, final products) used within the territory, however, they tend to consider only the flows of materials entering use while neglecting the role of in-use stocks in determining the levels of energy and material throughput required to construct, operate, and maintain them. We demonstrated that infrastructures represent large reservoirs of materials and embodied emissions and that their spatial configuration and the age structure determine the annual throughput of material and energy required for their construction, operation, and maintenance. Emissions inventories that consider only flows provide limited information about infrastructure stocks and their role in the socio-economic metabolism, which is necessary to develop design principles for new settlements that deliver high standards of living while reducing overall emissions. Furthermore, they do not allow for a fair and meaningful comparison between growing, mature, or shrinking cities. Including information about the development of stocks in emissions inventories would allow policy makers to develop more realistic benchmarks and more effective strategies for the construction, use, and maintenance of settlements with minimal overall carbon emissions.

The different levels of built environment stocks among countries define crucial challenges and opportunities for climate change mitigation. Generally, industrialized countries dispose of large infrastructure stocks, which results in a substantial advantage for saving indirect emissions compared to industrializing countries, where stocks yet have to be built up. On the other side, existing infrastructures often represent lock-ins for direct emissions, which may only be reduced by replacing or retrofitting these structures using additional materials. However, countries with a need for replacing existing infrastructures also have a potential to use the obsolete structures as a source of secondary materials (urban mining and recycling), which can save substantial amounts of emissions. In contrast, developing countries first have to build up their infrastructure stocks, which, involves opportunities for leapfrogging on the side of production technologies as well as urban form and structure (material use). These different boundary conditions for development and mitigation options have consequences for redefining the principle of "common but differentiated responsibilities" and must be considered appropriately to engage developing countries in a fair and effective climate change policy architecture for the post-Kyoto era.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Methodology, data sources, and data treatment are documented in the Supporting Information SI-1. The results for in-use-stocks of cement, steel, and aluminum as well as the data behind Figure 4 are compiled in a set of spreadsheets (SI-2). This material is available free of charge via the Internet at http://pubs.acs.org.

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Author Contributions

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■ ABBREVIATIONS

CO_2-eq	carbon dioxide equivalent
CRV_{P2008}	carbon replacement value based on primary production in 2008
Gt	gigatons

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