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COMMENTARY:

Urban infrastructure choices structure climate solutions

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Cities are becoming increasingly important in combatting climate change, but their overall role in global solution pathways remains unclear. Here we suggest structuring urban climate solutions along the use of existing and newly built infrastructures, providing estimates of the mitigation potential.

Cities and other human settlements are important drivers of greenhouse gas (GHG) emissions, and contribute to mitigation actions world wide[1,2]. At the same time, carbon polluting activities and response measures to these are most tangible where people live and settle. However, the explicit representation of the urbanization process is consistently overlooked in global scenarios depicting solution pathways to mitigation. While urban transport and buildings are captured as part of sectoral approaches, the relevance of urban solutions within the global context remains obscure. This absence is rooted in the limited availability of consistent data, difficulty in synthesizing a heterogeneous body of literature, and reliance on only a few place-specific variables. In addition, global models induce climate mitigation by a generic policy instrument such as carbon pricing. This is inadequate to capture urban solutions, which are set apart by their built environment, and especially by the transport and building components of urban infrastructures. The built environment shapes and structures everyday life of its citizens specifically, and humanity generally. Urban infrastructure provides important boundary conditions — influencing the mitigation potential of energy efficiency improvements or lifestyle changes. Hence, an improved understanding of climate policy solutions hinges on progress in explicitly integrating human settlements in research on global emission pathways, presenting a core challenge for the upcoming sixth assessment cycle of the IPCC where urban-scale mitigation will take centre stage. To make urban solutions analytically accessible, mitigation opportunities need to adequately represent the importance of the built environment in cities worldwide. This would enable a mapping of established policy options on classes of urban infrastructures, demonstrating their importance across spatial scales.

The focal role of urban infrastructures

For a given level of economic wealth and economic structure, urban infrastructures are central to explaining urban GHG emissions. Evidence suggests that differences in the type and shape of the built environment can result in differences in urban transport and residential GHG emissions by a factor of ten[3]. For example, a low-carbon city typically features: relatively high-density households and population; mixed residential use, workplaces, retail, and leisure activities; a high number of intersections; and mobility choices that avoid excessive construction of low-connectivity roads[1,4].

Furthermore, critical boundary conditions for climate change mitigation are determined by urban infrastructure because of its longevity and carbon-intensive nature. Among all long-lived capital stocks, land use, urban form and road systems stand out for their century-long endurance, exceeding the lifetimes of coal power plants and car fleets. This introduces inertia into efforts to modify GHG emission patterns. Additionally the construction of new infrastructure could consume a considerable share of the remaining carbon budget as it is a carbon-intensive process. In fact, these upfront GHG emissions from infrastructure construction explain some of the emissions surge in China during the 2000s, representing 61% of emissions growth between 2005 and 2007[5].

Therefore, we suggest that urban climate solutions should be structured along infrastructures, and emissions and associated solutions should be divided into three distinct classes: by use of existing infrastructure; by use of new infrastructure; and by construction of infrastructures. We synthesize published data and calculate order of magnitudes of current and future emissions for each of these three infrastructure classes (Tables 1 and 2).

For existing urban infrastructures, we estimate that their use amounts to approximately 9.6 $GtCO_2e$ annually (20% of global anthropogenic GHG emissions), with about 6.8 $GtCO_2e$ (70%) from

Table 1 | Estimated annual emissions in 2010 in $GtCO_2$.

	Mean	Range	Source/computation
Urban buildings	6.8	1.6–4.6	Overall building emissions are 9 $GtCO_2$ (range: 6–14.5 $GtCO_2$) in 2010[6,7]. If urban building emissions scale similar to urban final energy use (76% of all final energy use[1]) then urban buildings emissions amount to 6.8 $GtCO_2$ in 2010.
Urban transport	2.8		Urban transport is estimated to contribute 40% of transport sectoral emissions[13].

Table 2 | Total expected emissions 2016–2030 in $GtCO_2$. Urban mitigation considers infrastructure solutions. Technological decarbonization options and trends are not included.

	BAU	Urban mitigation	Mitigated CO_2 (2050) / BAU CO_2 (2050)	Source/computation
Existing infrastructures	210	155–188	0.10–0.26	20–50% in urban transport[8]. 30–60% in buildings[6].
New infrastructures	495	158–272	0.45–0.68	As above but with 25% more efficient urban form[11].
Construction of infrastructures	268	248	0.07	Based on ref. 14, not considering carbon capture and storage for cement. See also Fig. 1.
Total	**973**	**561–708**		

BAU, business as usual.

Table 3 | For comparison with Tables 1 and 2: remaining emission budgets in $GtCO_2$.

	Min.	Max.	Source/computation
1.5 °C	0	220	Based on ref. 16.
2 °C	550	1,200	Based on ref. 16.
INDC 2016–2030	600		Based on ref. 16.

INDC, intended nationally determined contributions.

buildings and 2.8 $GtCO_2e$ (30%) from urban transport (Table 1) urban buildings and urban transport; indirect effects from consumption and emissions from industrial processes and waste are excluded from the analysis): mitigation from existing infrastructure is challenging as buildings often have lifetimes longer than 40 years; for transport structures, lifetimes can span centuries. Using state-of-the-art design principles (for example consideration of building orientation, form, thermal mass; building envelope design to reduce heating and cooling load; maximization of passive heating, cooling, ventilation, and daylight) to replace the current building stock could lead to up to 90% lower emissions[6], while retrofitting with energy conservation measures could reduce emissions of existing stock by about 30–60%[7]. In addition, modal shift driven by city tolls and improved public transit systems could reduce urban transport emissions by 20–50% compared to baseline in 2050[8]. Together, transport and building solutions would enable a 27–57% reduction in GHG emissions compared to the baseline (Fig. 1).

In business-as-usual scenarios, the in-use emissions of infrastructures newly built after 2015 exceed 10 $GtCO_2$ per year in 2030[9]. Thus the use of new infrastructures could quickly consume the remaining carbon budget that is associated with likely ($p > 66\%$) keeping warming below 2 °C relative to pre-industrial levels[10]. Overall, two key classes of measures — both urban planning, for medium to high residential and job density, and transport pricing, applied to new infrastructures — could reduce future energy use of global cities by about 25% relative to business-as-usual, with most of this reduction in Asia and Africa[11]. Importantly, such measures would primarily address transport emissions by shortening travel distances and enabling low-carbon transport modes, but could indirectly affect emissions from the building sector by incentivizing the construction of higher density housing and reducing per capita floor space[11,12]. Together with existing infrastructures options, emissions could be reduced by 45–68% (Fig. 1). Urban energy systems, such as rooftop photovoltaics, could supply 8% of urban energy consumption economically by 2050[13], adding to the mitigation potential.

If per capita infrastructure provision in developing countries converges to the level found in developed countries, emissions will increase by 350 $GtCO_2$ by 2050, or by 9.2 $GtCO_2$ per year, if calculated using current standards and technology[14]. Alternative standards and technology include building less, using less floor space per person, using materials with lower carbon intensity, and reducing emissions from the production of cement and steel (about 13% mitigation, and >90% with carbon capture and storage for cement, Fig. 1). The scale of infrastructure emissions associated with both lifetime usage and its construction necessitates their detailed consideration in models of urbanization and its GHG emissions.

The three classes of urban infrastructure emissions all contribute significant amounts of GHG emissions, but it is the use of infrastructures to be built in the next fifteen years that is decisive in determining emissions in 2030 (Fig. 1). Together these three classes have the potential for infrastructure-based mitigation measures to reduce energy demand by more than half compared to a business as usual scenario. However, while annual emission rates would decline significantly, the total GHG emissions originating from urban infrastructure alone would be sufficient to consume the remaining budget for the 1.5 °C target, and would consume a large fraction of the 2 °C budget (Tables 1–3). Therefore, energy efficient urban infrastructure solutions are necessary to reach climate goals, but are clearly insufficient in the absence of low-carbon energy sources.

Implementing city typologies

To capitalize on the potential mitigation opportunities in urbanization requires detailing the solution space along the three distinct classes (use of existing and new infrastructures and construction of new infrastructures). Due to the scales involved,

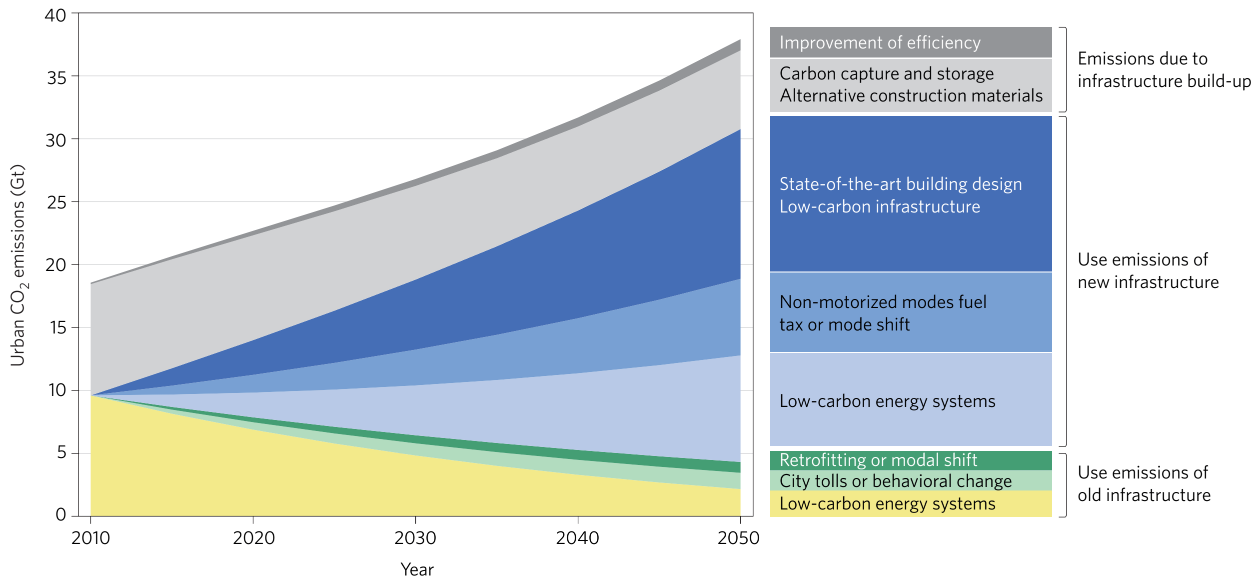

Figure 1 | CO_2e emissions from the three different urban categories. Total annual emissions from old urban infrastructure use (yellow) amount to 6.8 $GtCO_2$ (70%) and 2.8 $GtCO_2$ (30%) in buildings and transport respectively in 2010. This infrastructure is assumed to have a mean lifetime of 50 years: its impact diminishes only slowly (lock-in). The use emissions of new infrastructure (blue) constitute the major part of future emissions. Emissions due to infrastructure build-up (grey) constitute the third part. As a benchmark case, a convergence scenario assumes that infrastructure is continually replaced in more developed countries at a constant level while in less developed countries, infrastructure is replaced at levels of more developed countries. Infrastructure for new urban population is constructed at levels of more developed countries. For data see Tables 1 and 2.

steering the ongoing urbanization processes in Asia, the Middle East, and Africa towards efficient infrastructures is necessary to ensure urbanization makes a relevant contribution to global mitigation. Solution strategies can be adapted to city types, based on city typologies that report meaningful co-occurrences of urban form, economic, and local climate parameters[11,15]. Around half of the mitigation potential hinges on urban form and building design and mode shift (Fig. 1), so the resulting climate solutions will also be invested in resilience to climate change, and to quality of life. This requires economic and technical solutions like taxes on fuels, inner city tolls, and public transport infrastructures that are complemented by city design for people, including enjoyable public spaces, green space access, and high connectivity for walking and cycling. Importantly, transport infrastructure is critical, because it also influences building solutions[11,12]. At the same time, to make best use of emerging technologies — such as electric bikes and cars, autonomous vehicles, shared vehicle fleets and smart metering — policies must make sure that these technologies supplement rather than complement dirty technologies, and render the use of infrastructures more efficient.

The ongoing global urbanization trend underlines a window of opportunity for considerable climate mitigation by urban infrastructure design. A large share of urban infrastructures is yet to be built and their design will distinctively determine the feasibility of meeting ambitious mitigation goals. A key challenge is that many of the most rapidly developing cities, notably cities of less than one million inhabitants, particularly in Asia and Africa but also in North America, Europe, and Australia, lack capacity for urban planning and the strong institutions required to enforce it. Researchers could improve the knowledge base by focusing more on smaller cities, and development banks could increasingly bundle and finance infrastructure solutions in small and medium-sized cities. Comparative analysis and policy dissemination on urban scales is hence crucial for reaching ambitious climate targets. With low-carbon urban infrastructure in place, prospects of meeting global mitigation goals will look much brighter. ❐

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