

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, climate polluting activities and response measures to these are most tangible where people live and settle. Yet, 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 the reliance on only 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 center 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 ten³. For example, a low-carbon city typically features A) relatively high-density households and population, B) mixed residential use, workplaces, retail, and leisure activities, C) a high number of intersections, and D) mobility choices that avoid excessive construction of low-connectivity roads^{1,4}.

Further, 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 up-front GHG emissions from infrastructure construction explain some of the emission surge in China during the 2000's, representing 61% of emission growth between 2005 and 2007⁵.

Therefore, we suggest that urban climate solutions should be structured along infrastructures, and emissions and associated solutions should be divided into three distinct classes:

- A) by use of existing infrastructure;
- B) by use of new infrastructure; and
- C) 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 (Tab. 1).

For existing urban infrastructures, we estimate that their use amounts to approximately 9.6GtCO₂e annually (20% of global anthropogenic GHG emissions), with about 6.8GtCO₂e (70%) from buildings and 2.8GtCO₂e (30%) from urban transport (Tab. 1A; 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 of longer than 40 years, and transport structures of 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 emissions⁶, 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 2050⁸. Together, transport and building solutions would enable 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 10GtCO₂ per year in 2030⁹. 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 levels¹⁰. Overall two key classes of measures - urban planning and transport pricing — applied to new urban infrastructure could reduce future energy use of global cities by about 25% relative to the baseline, with most of this reduction in Asia and Africa¹¹. 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 2050¹³, adding to the mitigation potential.

The building of infrastructures itself also causes GHG emissions. Closing the infrastructure gap in developing countries to be a similar standard with developed countries, could increase emissions by 350GtCO₂ by 2050, or by 9.2GtCO₂ per year, if based on current standards and technology¹⁴. 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 CCS 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 business as usual. 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 (Tab. 1). Hence, 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 capitalise on the potential mitigation opportunities in urbanization requires detailing the solution space along the three distinct classes (use of existing, use of new, and construction of new infrastructures). Due to the scale, 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 into resilience to climate change, and to quality of life. This requires that economic and technical solutions like taxes on fuels, inner city tolls, and public transport infrastructures are complemented by city design for people, including enjoyable public spaces, green space access, and high connectivity for walking and cycling. Importantly, transport infrastructures would be focal, which indirectly 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 trends 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 prospects 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 OECD countries, 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 help building capacity and financing small and medium-scale infrastructure solutions.

Comparative analysis and policy dissemination on urban scale 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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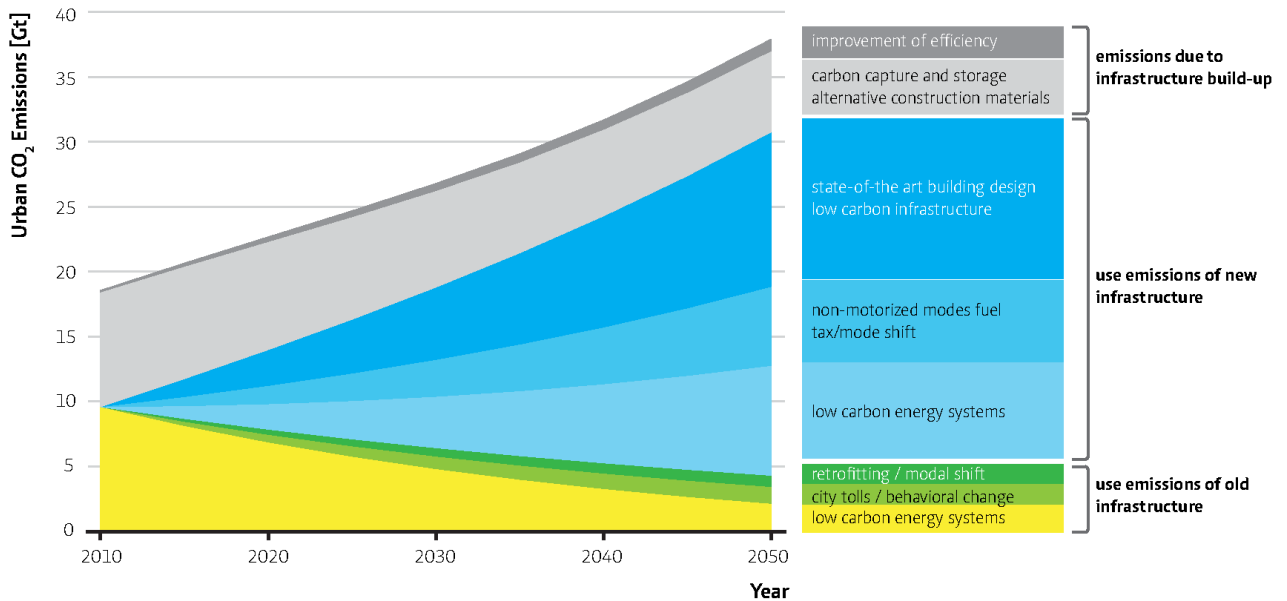


Figure 1. CO_{2e} emissions from the three different urban categories. Total annual emissions from old urban infrastructure use (yellow) amount to 6.8GtCO₂ (70%) and 2.8GtCO₂ (30%) in buildings and transport respectively in 2010. This infrastructure is assumed to have a mean lifetime of 50 years: its impact diminishes only slowly (lock-in). Only a fraction of about 20-50% of those emissions can be mitigated in the long term¹¹. The use emissions of new infrastructure (blue) constitute the major part of future emissions. Emissions due to infrastructure build-up (gray) constitute the third part. As a benchmark case, a convergence scenario assumes that infrastructure is constantly replaced in more developed countries at 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 Tab. 1.

Table 1. Urban emission accounting A. Estimated annual emissions in 2010. B. Total expected emissions 2016-2030. Urban mitigation considers infrastructure solutions. Technological decarbonization options and trends are not included. C. For comparison, remaining emission budgets.

A	Estimated GtCO ₂ from urban sources 2010		Source / Computation	
	Mean	Range		
urban buildings	6,8	4,6-10,6	Overall building emissions are 9GtCO ₂ (range: 6-14.5 GtCO ₂) in 2010, reported by ^{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 6.8GtCO ₂ in 2010.	
urban transport	2,8		Urban transport is estimated to contribute 40% of transport sectoral emissions ¹³	
B	Total Urban Emissions 2016-2050 in GtCO ₂			Source / Computation
	BAU	Urban mitigation	Mitigated CO ₂ 2050 / BAU CO ₂ 2050	
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 ¹⁴ , not considering CCS for cement. See also caption of Fig. 1.
total	973	561-708		
C	Remaining carbon budget from 2016 (range)		Source / Computation	
	Min	Max		
1.5°C	0	220	Based on ¹⁶ .	
2°C	550	1200	Based on ¹⁶ .	
INDC 2016-2030	600		Based on ¹⁶ .	

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