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Low-carbon infrastructure strategies for cities

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Reducing greenhouse gas emissions to avert potentially disastrous global climate change requires substantial redevelopment of infrastructure systems[1-4]. Cities are recognized as key actors for leading such climate change mitigation efforts[6-10]. We have studied the greenhouse gas inventories and underlying characteristics of 22 global cities. These cities differ in terms of their climates, income, levels of industrial activity, urban form and existing carbon intensity of electricity supply. Here we show how these differences in city characteristics lead to wide variations in the type of strategies that can be used for reducing emissions. Cities experiencing greater than ∼1,500 heating degree days (below an 18 °C base), for example, will review building construction and retrofitting for cold climates. Electrification of infrastructure technologies is effective for cities where the carbon intensity of the grid is lower than ∼600 $tCO_2e\ GWh^{-1}$; whereas transportation strategies will differ between low urban density (<∼6,000 persons km^{-2}) and high urban density (>∼6,000 persons km^{-2}) cities. As nation states negotiate targets and develop policies for reducing greenhouse gas emissions, attention to the specific characteristics of their cities will broaden and improve their suite of options. Beyond carbon pricing, markets and taxation, governments may develop policies and target spending towards low-carbon urban infrastructure.

Over the past five years we have undertaken a sustained effort to conduct greenhouse gas (GHG) inventories for city regions (hereafter cities) using a consistent methodology[11]. This has included study of ten global cities[12], incorporating Chinese[13] and low- to middle-income cities[14], analysis of Paris-Isle de France and the Chicago region for the Organization for Economic Cooperation and Development[15,16]; and further city inventories based on urban metabolism studies[17]. The method used is generally similar to that employed or reported by others[18–20] being an adaptation of the Intergovernmental Panel on Climate Change (IPCC) production-based approach for nations, including some transboundary (scope 2 and 3) emissions. For the city inventories in our work we include scope 3 emissions for aviation, marine and waste (Fig. 1) whereas other studies have included either more or fewer scope 3 emissions (see ref. 21 for comparison of methodologies). These studies have helped to establish the main sources of GHG emissions attributable to cities—transportation, energy use in buildings, electricity consumption and, to a lesser extent, waste and industrial processes—as well as the driving factors underlying the emissions. The breadth of cities studied has also revealed variations in the type and magnitude of city emissions. Consequently, as we discuss here, cities will use a wide variety of situation-specific strategies to reduce their emissions.

The 22 cities that we study here differ considerably in terms of affluence. There is a general trend of increasing per capita emissions with per capita gross domestic product

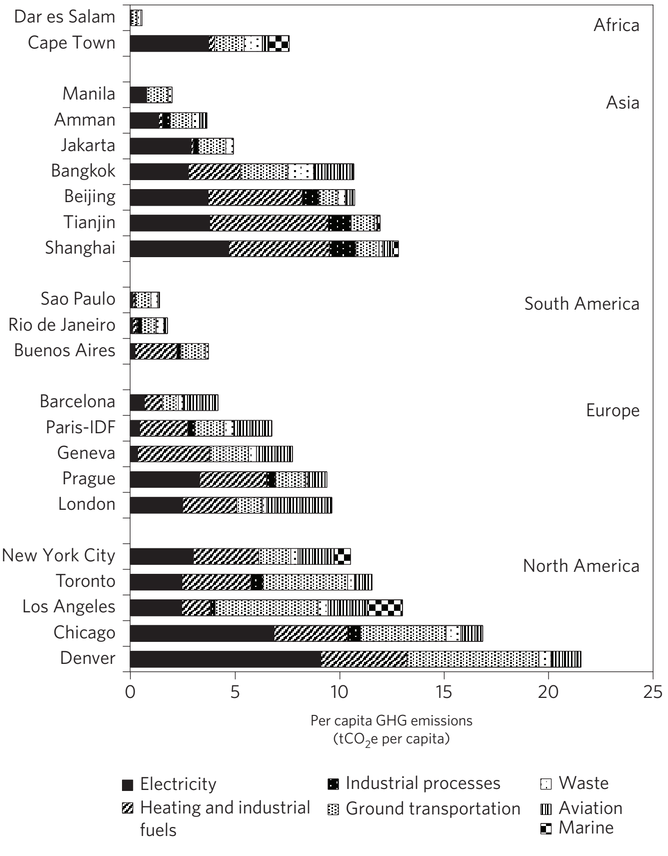

Figure 1 | Per capita GHG emissions for cities, by continent.

(GDP), although with substantial variability (Fig. 2). Of the eight cities with emissions under 5 tCO_2e per capita, only Barcelona has a GDP per capita greater than US$20,000 (purchasing power parity, PPP). Bangkok and the three Chinese cities, however, have emissions of more than 10 tCO_2e per capita with per capita GDP of less than US$20,000. The wealth of cities is a factor in explaining their amounts of GHG emissions—and will also impact their ability to afford various emissions reduction strategies.

Another factor that impacts on urban GHG inventories is climate, which influences building energy use in particular. Figure 3 shows increasing energy use per capita for the combustion of fuels in heating buildings and industry in relation to heating degree days. Clearly colder cities have higher building heating demands. There is some variation about the trend-line, which probably can be attributed in part to industrial combustion, but we do not have the data differentiated by type of end user. Building retrofit

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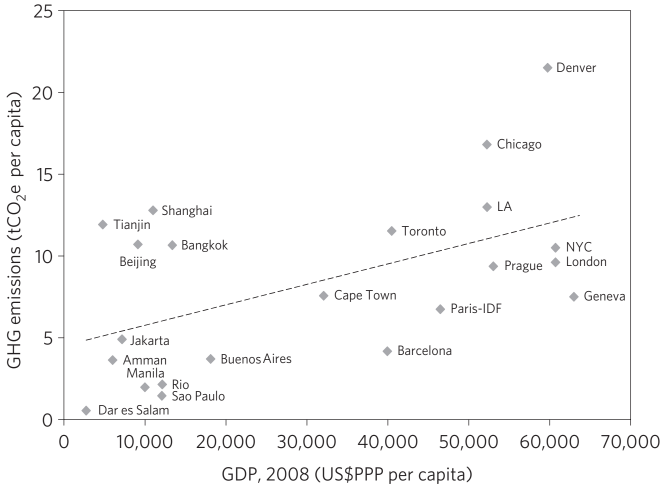

Figure 2 | Per capita GHG emissions and per capita GDP (2008, US$PPP) for the 22 cities.

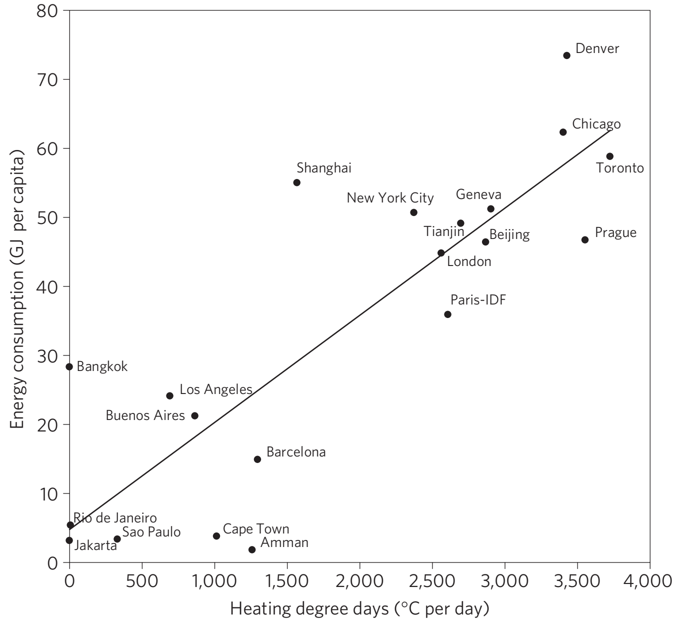

Figure 3 | Per capita energy consumption of heating and industrial fuels in relation to heating degree days (18 degree base).

strategies are expected to differ between cities in cold, temperate and hot climates. When it comes to new buildings, however, there is some evidence that the energy intensity of high-performance green buildings no longer correlates with climate[22]. Energy-efficient buildings moderate the interface between the interior and the exterior climate more efficiently, employing methods such as active and passive solar building design[23], nested enveloped and super-insulated envelopes, and others.

The GHG emissions associated with building heating and industrial combustion also depend on the emission intensity of the type of fuel. Fuel switching is a strategy that can be employed—and is common among cities recording reductions in emissions[24]. More advanced strategies include use of thermal energy storage systems or ground-source heat pumps (GSHPs), although use of the latter can lead to increased emissions if the carbon intensity of the electricity grid is high[25]. Attention to emissions from the combustion of fuels is clearly more important in cold cities such as Prague and industrial cities such as Shanghai—both using substantial quantities of coal and oil—than in warmer cities such as Cape Town and Sao Paulo.

Climate is also a factor in electricity consumption in cities, although the emissions intensity of the local supply generally has a greater impact on overall emissions. Per capita electricity consumption for the cities in Fig. 1 range from as low as 0.16 MWh per capita for Dar es Salaam, the poorest city, to 9–10 MWh per capita for Chicago, Denver and Toronto, with interior continental climates. Most of the cities, however, have electricity consumption in the range of 2–7 MWh per capita. A greater contribution to emissions comes from the emissions factor, which is close to 1,000 $tCO_2e\,GWh^{-1}$ for cities such Beijing, Tianjin and Cape Town, with coal intensive electricity, and as low as 50–100 $tCO_2e\,GWh^{-1}$ for cities such as Geneva and Paris, largely supplied by hydro or nuclear power.

With respect to GHG emissions from ground transportation, three broad groupings of cities are apparent. The low-density North American cities (excluding New York City) have emissions greater than 4 tCO_2e per capita. The low-density, low- to middle-income cities of Amman and Dar es Salaam have emissions under ~1 tCO_2e per capita. Whereas the higher density cities (>6,000 persons km^{-2}—based on urbanized area) have emissions under 2 tCO_2e per capita, except for Bangkok at 2.27 tCO_2e per capita. Within any of the groupings, density may be a secondary factor to land use, urban design and provision of transit in explaining emissions, but it is a primary factor when considering the overall group of cites as a whole.

Electrification of technologies is widely considered for reducing emissions, but its success depends on the carbon intensity of electricity supply. A study of electric vehicles and plug-in hybrid vehicles, for example, has shown that these vehicles yield lower life-cycle GHG emissions in eight of ten regions of the United States[26]. The region at which electric vehicles just become carbon competitive against gasoline vehicles in the US study has a grid intensity of 700 $tCO_2e\,GWh^{-1}$. In a similar European study, electric vehicles were determined to have approximately equal life-cycle emissions to a conventional diesel vehicle at a grid intensity of 643 $tCO_2e\,GWh^{-1}$ (ref. 27). So although there are differences due to vehicle characteristics, the threshold grid intensity at which electric vehicles become carbon competitive is of the order 600–700 $tCO_2e\,GWh^{-1}$.

Replacement of building furnaces with heat pumps, such as ground source or air source, is another strategy involving electrification, in this case to power the pumps. A previous study[25] determined that replacement of natural gas furnaces with GSHPs in residential homes in Canadian cities can reduce emissions when the carbon intensity of the grid is sufficiently low. This strategy is carbon competitive in Montreal, Ottawa, Toronto and Vancouver, but not in Calgary. For a typical heat pump with a coefficient of performance of 2.5–3.0, replacing a natural gas furnace, GHG emissions are reduced at grid intensities of less than 500–600 $tCO_2e\,GWh^{-1}$. There will be some variation in the grid intensities at which various electrification strategies (electric vehicles, GSHPs and others) are competitive, warranting further study, but the key threshold is around 600 $tCO_2e\,GWh^{-1}$.

The GHG intensity of existing electricity supply and urbanized population density can be used to broadly demonstrate how cities will prioritize different low-carbon infrastructure strategies for reducing emissions (Fig. 4). Cities can be grouped into four sectors of Fig. 4 approximately defined by the GHG intensity of 600 $tCO_2e\,GWh^{-1}$ and an urban density of 6,000 persons km^{-2}. Although some of the strategies can be applicable to more than one sector of the graph, the most appropriate sectors (economically and in terms of emissions reductions) are shown. With respect to reducing transportation emissions, low-density cities may become more compact in the long run, but in the short term they typically have insufficient population density to support financially viable

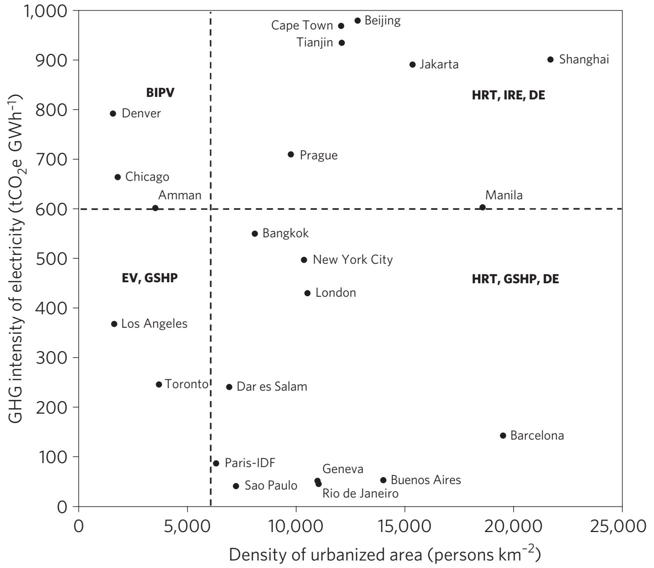

Figure 4 | Examples of low-carbon infrastructure strategies tailored to different cities. Prioritization according to urban population density and the average GHG intensity of existing electricity supply. EV, electric vehicle; GSHP, ground-source heat pumps; BIPV, building integrated photovoltaics; HRT, heavy rapid transit; IRE, import renewable energy; DE, district energy.

heavy rapid transit systems. Adoption of electric vehicles (of various varieties) may be more pressing in these cities and particularly effective in those with low-carbon electricity supply. Although density is not uniform within a single city, buildings in low-density cities will generally have greater solar access than high-density cities, thus possibly making them more suitable for widespread application of building integrated photovoltaics (BIPV); emissions reductions per dollar invested will be greatest where the carbon intensity of electricity supply is highest. Investment in district energy systems will typically be more financially prudent in high-density cities, where piping costs per capita are lower. Where suitable conditions exist, widespread use of GSHPs can be a relatively cost-effective energy strategy, but GHG emissions will be reduced only where the electricity used to run the pumps is of a low- to medium-carbon intensity.

Overall, we demonstrate here the congruence of cities developing low-carbon infrastructure strategies that reflect their unique characteristics. Climate change action in cities plays out in a multilevel governance context[5]. At the national level much of the focus of governments is on carbon pricing, markets and taxation, but in a multilevel context, governments can develop urban policies and target spending towards low-carbon urban infrastructure. This means going beyond the selection of strategic actions based on marginal abatement costs and pursuing actions that are more appropriate and effective given the characteristics of cities such as climate, industry, urbanized density and electricity supply.

The use of situation-specific strategies to reduce GHG emissions has proliferated in cities and there is a lot to learn among cities of comparable population densities, climates, energy mix and behaviours in transportation and building-related energy-consumption patterns. Although urban climate action continues to grow, evidence of the effectiveness of these measures remains limited[6,24]. The feasibility of low-carbon strategies will be better determined if cities look beyond their neighbours, as well as experimenting with successful urban climate governance models. Shifting away from the dependence on fossil fuels, promoting energy efficiency and increasing the price of energy are effective measures to reduce emissions, although the prioritization of such strategies depends ultimately on the wealth of the cities and its residents, and the advancement of climate change on the city agenda. The geographic reach of cities in this work reflects also the range of affluence of cities, which are engaged in the process of development or further urbanization, and to which the pathways to low-carbon economies will evidently differ. Well-structured urban climate governance could be a tool to determine how the cost burden of such strategies will fall on local governments, businesses and individuals. The comparative nature of this study allows local governments to focus on the drivers of emissions and set commitments to prioritize climate action and pursue emission reductions.

Methods

Definition of city regions. Most of the cities studied are metropolitan regions, that is, commutersheds comprising common labour and housing markets; these are often, but not necessarily, contiguous urban regions (Supplementary Table 1). There is no common globally accepted way of defining metropolitan regions; and in practice data are available for areas defined by local or regional political boundaries. In a few cases, for example, Barcelona and New York City, the boundaries used were those of a central municipality within a larger metropolitan region; in these cases the per capita transportation emissions will typically be lower than those of the larger region.

GHG inventories. The city GHG inventories are determined by bottom-up calculations similar to the method used by nations under the United Nations Framework Convention on Climate Change[11]. Emissions are calculated by multiplying activity levels (for example, quantity of fuel combusted) by emissions factors (for example, emission per quantity of fuel combusted). The activity levels are collected from local data sources (Supplementary Table 7) with emission factors from the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. The city GHG inventories differ from the pure production-based approach for nations in that they include emissions that occur outside of cities as a result of activity drivers inside cities (scope 2 and 3 emissions). The emissions shown in Fig. 1 include: scope 2 electricity emissions based on electricity consumption in cities, plus transmission and distribution losses; scope 3 emissions from waste, when this is exported from cities; and scope 3 aviation and marine emissions, based on fuel loaded onto planes and ships within the boundaries of cities (data in Supplementary Tables 2–7).

City characteristics. Several measures are used to explain differences between cities' emissions and develop strategies for reducing emissions. Values of per capita GDP for 2008 are provided for all but four cities by Price Waterhouse Coopers in Appendix 10 of the World Bank's Building Sustainability in an Urbanizing World report[28] (sources for Amman, Denver, Geneva and Prague are given in Supplementary Table 1). Heating degree days were determined from http://www.degreedays.net/ using data at city airports, with an 18° C base. Population densities for urbanized areas are calculated excluding areas of agriculture, large parks and other undeveloped areas within city boundaries; values are mostly determined from local sources (Supplementary Table 6).

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Author contributions

C.A.K., N.I. and D.H. co-wrote the paper; C.A.K. and N.I. conducted the analysis.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to C.A.K.

Competing financial interests

The authors declare no competing financial interests.