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Keeping cities green: Avoiding carbon lock-in due to urban development

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C40 CITIES
CLIMATE LEADERSHIP GROUP

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ABSTRACT

Cities around the world are emerging as leaders in the fight against climate change, embracing low-carbon transport, high-efficiency buildings, renewable energy and other strategies to reduce emissions while building more vibrant urban communities. At the same time, urban areas are growing astoundingly fast: 1.4 million new urban dwellers each week, and with corresponding demands for energy, goods, and services. Therefore, how our cities are built is a critical factor in the intensity of urban energy use. From the types of housing and commercial buildings, to our road networks and transport systems, to how we get our heat and power, urban infrastructure determines, to a great extent, whether a city has high or low greenhouse gas emissions. Here, we look at two scenarios of urban development over the next 15 years. We find that, in the reference scenario, new, energy-inefficient urban development may substantially "lock in" future CO_2 emissions, as roughly 30% of future CO_2 emissions "committed" annually occur due to new, urban building and transport systems. However, in an aggressive "urban action" scenario, urban policy-makers can instead deploy the most energy-efficient technologies and urban design, and avoid committing about 45 Gt CO_2 of cumulative future emissions. Making these choices now, instead of attempting costlier retrofits later, can substantially lower the cost of meeting stringent climate objectives for cities and nations alike. At the same time, retrofitting of existing infrastructure – urban and otherwise – is also necessary to "unlock" the existing roughly 800 Gt CO_2 of emissions already "committed" and help keep emissions within the 1,000 Gt CO_2 carbon "budget".

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1. INTRODUCTION

Cities around the world are emerging as leaders in the fight against climate change, embracing low-carbon transport, high-efficiency buildings, renewable energy and other strategies to reduce emissions while building more vibrant urban communities. Yet urban areas are growing astoundingly fast: 1.4 million new urban dwellers each week (UN 2014), with corresponding demands for energy, goods, and services.

How our cities are built is a critical factor in urban energy use. From the types of housing and commercial buildings, to our road networks and transport systems, to how we get our heat and power, urban infrastructure determines, to a great extent, whether a city's energy use is relatively high or low, and the corresponding greenhouse gas emissions.

If not built to stringent low-carbon standards, urban infrastructure can also be a prime example of the phenomenon of *carbon lock-in* – when long-lived, energy and carbon-intensive assets persist, often for decades, and lock out more efficient, lower-carbon alternatives. Once constructed, urban infrastructure, such as buildings and transport systems, can continue to emit CO_2 directly (e.g. gas-powered furnaces) or indirectly (e.g. urban sprawl that makes people dependent on their personal cars) for many years.

Infrastructure that uses energy inefficiently will make it costlier and less likely that cities, and indeed, the world, can meet ambitious CO_2 reduction and climate protection goals. This is because, as more emissions are released in the near term, *even more* need to be reduced later, and at higher cost, since inefficient infrastructure must be taken out of service (or be retrofitted) later. For example, the International Energy Agency found that if less-efficient technologies are chosen in the near term instead of low-carbon alternatives, the longer-term investment cost needed to meet low-carbon objectives in power, buildings, industry, and transport sectors will quadruple (IEA 2013b). Furthermore, by continuing to build less-than-optimal infrastructure – urban or otherwise – planners further entrench less-efficient technologies, as well as the social and political institutions that support them, instead of low-carbon alternatives and their respective institutions (Erickson et al. 2015a; Whitelegg 2015; Driscoll 2014).

Considering the increasing prominence of cities as important contributors to low-carbon development (Seto et al. 2014; Global Commission on the Economy and Climate 2014; Ewing et al. 2008), this paper aims to quantify the current rates of urban carbon lock-in.

Our analysis builds on a recent assessment of urban greenhouse gas emissions pathways, conducted in partnership with the UN Special Envoy for Cities and Climate Change and C40 Cities. That analysis, which in turn built on research by the IEA and other sector-focused research institutions, constructed two scenarios. The first, a reference scenario, showed how urban GHG emissions globally may evolve over the next three decades if only incremental, already-expected technologies and practices emerge. The second, a low-carbon "urban action" scenario, showed how emissions could be reduced if urban policy-makers take bold and aggressive action to reduce GHG emissions.

This analysis takes a new look at those two scenarios. Specifically, we calculate the annual and cumulative, long-term CO_2 emissions implications – the "committed emissions" – of new investments in infrastructure and equipment in each scenario. These technologies, unless dramatically refurbished or retired early, could lock in GHG emissions for years or decades to come. This analysis quantifies those long term, locked-in CO_2 emissions, and shows how they fit with the 1,000 Gt CO_2 global carbon budget allowed to maintain the chance of limiting warming to 2°C (Clarke et al. 2014). We then look at how aggressive urban action through 2030 can contribute to keeping emissions within this carbon budget.

Our findings can inform both local and national policy. City policy-makers may use this information to help identify those actions that most lock cities into high-carbon pathways in the long term, increasing eventual abatement costs and making it harder to achieve the stringent low-carbon objectives to which many cities have committed (Arup and C40 Cities 2014). National policy-makers may use this information to direct policy and financial support to help steer cities steer away from these high-carbon pathways.

We begin by presenting an analytical approach for systematically assessing carbon lock-in risks in an urban context. We then discuss results, including how urban carbon lock-in contributes to the global carbon budget. We end with conclusions about the role of urban development in global low-carbon transitions.

2. ANALYTICAL APPROACH

In this analysis, we take a new look at the long-term CO_2 emissions implications of the world's infrastructure and equipment, with a special focus on urban infrastructure. (Hereafter, we will use the term *infrastructure* to mean both large, capital-intensive projects, such as buildings and road networks, as well as the equipment that operates within or on that infrastructure, such as heating systems, appliances and vehicles.) As in prior work (Erickson and Tempest 2014; Global Commission on the Economy and Climate 2014), we consider "urban" areas as defined by the UN Department of Economic and Social Affairs (UN 2011). We focus on urban infrastructure associated with buildings and transportation in particular, as these sectors account for a substantial share of urban GHG emissions and are much likelier to be under city leaders' control than, say, the power supply (Erickson et al. 2013).

Methods for assessing the long-term emissions pathways of jurisdictions are well established (Sathaye and Meyers 1995; Tirpak et al. 1995), though the vast majority of such analyses have focused on national or global scales. Relatively few analyses, however, have focused specifically on the emissions associated with infrastructure (Davis et al. 2010; Guivarch and Hallegatte 2011). Since the goal here is to show how new infrastructure (e.g. building equipment, vehicles, urban form, building shells) contributes to cumulative long-term CO_2 emissions, we follow two sequential, steps: 1) estimate rates of new infrastructure construction or deployment; and 2) count cumulative CO_2 associated with energy used by this infrastructure.

2.1 Estimate rates of infrastructure construction or deployment

This may include, for example, annual construction of new buildings or roads, or purchases of passenger vehicles. No global database of existing and planned energy infrastructure is known to exist, and so approximations must be made from other sources. To ensure a global, consistent analysis, we adapt scenarios from the IEA's *Energy Technology Perspectives* series (IEA 2014). Specifically, we use the "4DS" scenario as a baseline, reference case. This scenario assumes that countries of the world largely continue along current trends, and also pursue the policies and plans that they had adopted or announced through 2013, including emission reduction pledges made since the Copenhagen Climate Change Conference in 2009. (The scenario does not, however, include the more recent "intended nationally determined contributions", or INDCs, submitted for the Paris Climate Change Conference to be held in December 2015).

We adopt the IEA's infrastructure assumptions, where available, such as those for construction of new power plants. For other infrastructure, such as transport systems or new buildings, we make approximations based on information available from the IEA about existing stocks and lifetimes or replacement rates, or impute such from trends in activity, such as growth in passenger travel. We separate urban vs. non-urban infrastructure as previously (Erickson and

Tempest 2014). In short, residential building infrastructure (in floor area, m^2) is attributed directly within each country or region based on population; commercial building infrastructure is assigned mostly (about 90%) to urban areas (Ürge-Vorsatz et al. 2012); passenger vehicles are assigned based on an IEA study of urban mobility (IEA 2013a); smaller freight vehicles designed for final, "last leg" delivery are assigned to urban areas; and emissions from power plants are assigned to urban areas in proportion to electricity demand from urban buildings and transportation.

2.2 Count cumulative CO_2 associated with energy used by infrastructure

As noted above, here we adopt a different way of accounting for emissions than is commonly done. To any given year, we attribute the *future* CO_2 emissions associated with energy use by infrastructure put in place in that year, following the recent innovation of commitment accounting for CO_2 (Davis and Socolow 2014). For example, consider a car purchased in 2015 that emits 1 tonne of CO_2 per year. Assuming that car will run for another 10 years (e.g. an average vehicle lifetime of 10 years), we attribute 10 tonnes of CO_2 to that vehicle and to each vehicle purchased in the year 2015.

In this way, in any given year, we track the entire cumulative CO_2 emissions "commitments" of new infrastructure, and assuming that none are retired or significantly retrofitted before their average technical lifetimes, in keeping with existing definitions of commitment-based accounting (Davis and Socolow 2014). Since we start accounting in 2012, this emissions commitment can be directly compared to the Intergovernmental Panel on Climate Change (IPCC) carbon budget of 1,000 Gt CO_2, and we can track total commitments relative to this budget (again, assuming no early retirements).[1] Box 1 further describes how this commitment-based approach to emissions accounting differs from standard, annual accounting for emissions, as employed by national and subnational entities as well as in our prior analysis of the *urban action* scenario.

Assigning emissions to a particular piece of infrastructure or equipment is not always straight-forward. For example, though it is relatively simple to assign the future emissions from a vehicle to the year in which it was purchased, one might also consider the larger infrastructure, urban form or transport system that the vehicle operates within, and whether some share of the emissions associated with use of the vehicle should be attributed to them as well. Accordingly, one could consider that, though some emissions must be assigned to the decision to purchase a vehicle, the urban form (including the road network), and the availability (or lack) of other public and non-motorized transport alternatives, that were already in existence helped pre-determine the decision. This dynamic – where multiple factors work together to constrain future energy and emissions pathways – is central to the notion of carbon lock-in (Unruh 2000). For this reason, we introduce an approach to apportioning emissions committed by new buildings and transport infrastructure between energy-consuming equipment (e.g. vehicles, furnaces) and the larger, systemic factors (e.g. building shells, road networks and urban form) that condition how that equipment is deployed. Though the method we develop is conceptually still relatively simple, it represents one of the first attempts at attributing cumulative emissions to infrastructure decisions that play out over different time-scales.

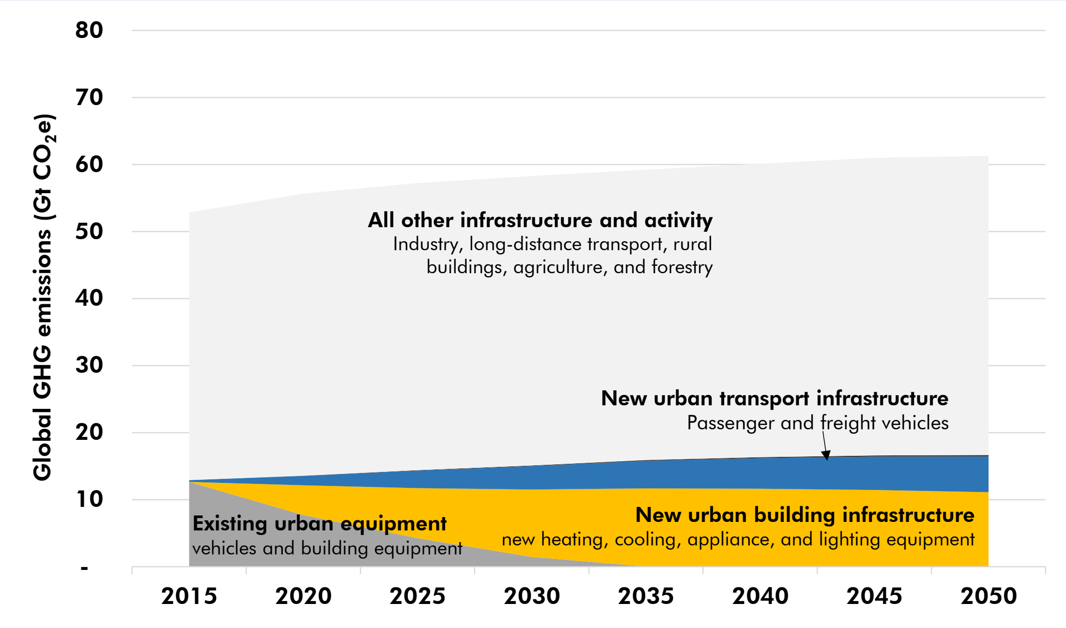
[1] IPCC Working Group I reports a cumulative carbon budget for the period 2012 to 2100 of about 1,000 Gt CO_2, and which is associated with a 66% chance of maintaining temperature increase of less than 2°C. The carbon budget of 1,000 Gt CO_2 is reflected in Table SPM.3, which displays cumulative emissions of 270 Gt C (990 Gt CO_2) for scenario RCP2.6 from 2012 to 2100 (IPCC 2013). Our estimates of committed emissions would therefore directly contribute to this carbon budget, except for any emissions that occur after 2100, though these are very small and occur only in long-lived buildings constructed in the later years (post-2020) of our analysis.

Comparing approaches to counting GHG emissions from infrastructure

The analysis presented in this report focuses on accounting for emissions commitments – that is, future emissions that will result from infrastructure existing today or put in place in any given year. This approach is helpful for two reasons. First, when focused on new infrastructure investments made in each year, it helps assign emissions to the year in which the action is taken to commit those future emissions, and so more clearly illuminates the future CO_2 emissions implications of near-term investment and purchasing decisions. Second, when combined with information on existing infrastructure, it helps track how much of the carbon budget may already be committed, which may create an additional incentive to avoid new carbon-emitting infrastructure or to undertake early retirement or major modifications of existing systems.

The figure below shows another way to understand committed emissions, using the traditional way of representing emissions on an annual basis, and is adapted from our prior, urban-focused report published in September 2014 (Erickson and Tempest 2014). Emissions associated with infrastructure, such as urban buildings and transport, are attributed on an annual basis, as they are released.

Figure 1: Emissions associated with infrastructure, 2015-2050 (in annual terms)



In the analysis presented in the remainder of this report, emissions from new infrastructure are instead attributed to the year in which they are committed. One could think of standing the lifetime emissions associated with new infrastructure in the figure above up on end, with separate columns for each year of new investment and that would, in total, add up to the same amount as the chart above (or, more accurately, the same amount as the chart above if the chart was extended rightward in time to include the full lifetime of infrastructure put in place between now and 2050.)

For new buildings, we assign to the initial building shell construction all emissions associated with building heating and cooling for the lifetime of the original heating system. We assume that future building owners and operators have an option to choose a different heating system at the end of the first system's lifespan, but are still largely constrained by the initial energy performance of the original building as built. We attribute emissions associated with these subsequent choices of heating replacement to the extent that they exceed those of the best (i.e. lowest-carbon) heating system projected to be available at the time in the corresponding scenario, with the remaining (best-available) level of emissions assigned to the upfront construction of the building. (For a diagram describing this concept, see Appendix A.)

For road-based transport systems, we assign emissions to one of two factors: urban form or vehicle purchase, as both lock in future vehicle use and emissions. We assume that expansion of urban form and the associated construction of new roads is primarily responsible for expansion of passenger vehicle travel,[2] therefore assigning emissions from net increases in passenger vehicle travel (and from vehicle travel enabled by replacement of road infrastructure) to decisions regarding urban form. We assign these road construction, or urban form, commitment emissions based on the lowest-carbon available vehicle technology, however, since people can still choose what types of vehicles they will drive on those roads. We assign commitment emissions associated with the choice of new vehicles to vehicle purchase, to the extent that these vehicles are more carbon-intensive than the best available technology (for net increases in vehicle travel), or at the full carbon intensity (for all other new vehicle travel, i.e. replacement of existing vehicles).

Error! Not a valid bookmark self-reference. describes these and other aspects of the method for attributing committed emissions to new infrastructure and equipment. We should note that urban jurisdictions also have substantial influence over waste management infrastructure (Erickson and Tempest 2014; Erickson et al. 2013). However, waste infrastructure, such as landfills, commits methane but also provides some long-term storage of carbon. Because methane does not contribute directly to the 1,000 Gt CO_2 carbon budget (that budget is for CO_2 only), and because methane commitments associated with waste are small (<2%) relative to commitments of CO_2 from buildings and transport infrastructure, we do not include waste management infrastructure here.[3]

[2] In cases where existing road networks are under-utilized, expansion of vehicle traffic may instead come from other factors, such as rising incomes or other behavioural factors.

[3] Long-term storage of carbon in landfills could be considered a commitment of negative CO_2 emissions, thereby subtracting from the carbon budget. Like methane commitments, this is small relative to energy-related CO_2 commitments from buildings and industry, and we do not consider it here.

Table 1: Method for attributing committed emissions to new infrastructure, equipment

Sector	Infrastructure or piece of equipment	Attribution of committed emissions for new infrastructure and equipment put in service
Buildings	Building shell (initial construction)	All emissions associated with building heating/cooling through normal first lifetime of heating/cooling system; subsequent emissions associated with lowest-carbon available heating/cooling system replacements through end of building lifetime. A modest level of natural improvement (e.g. via retrofits) is assumed over the building lifetime.
	Space heating and cooling	All emissions associated with replacement heating/cooling systems in building stock already-existing as of 2015; emissions in excess of lowest-carbon available heating/cooling system available at time of purchase (for buildings constructed in 2015 or later).
	Appliances and lighting	All emissions (direct fuel use and indirect power demand) associated with lifetime of new appliances and lighting.
Transport	Urban form (e.g. road networks)	Emissions associated with passenger and freight vehicle activity[4] on net expansion of urban form, as well as on replacement of road infrastructure, assuming lowest-carbon practical (e.g. readily available) vehicles deployed over the lifetime of the infrastructure (50 years).
	Vehicle choice	All emissions associated with the lifetime of new vehicles, except for net increases in travel (or as enabled by replacement of road infastructure), in which case attributed at level in excess of the lowest-carbon practical vehicle.

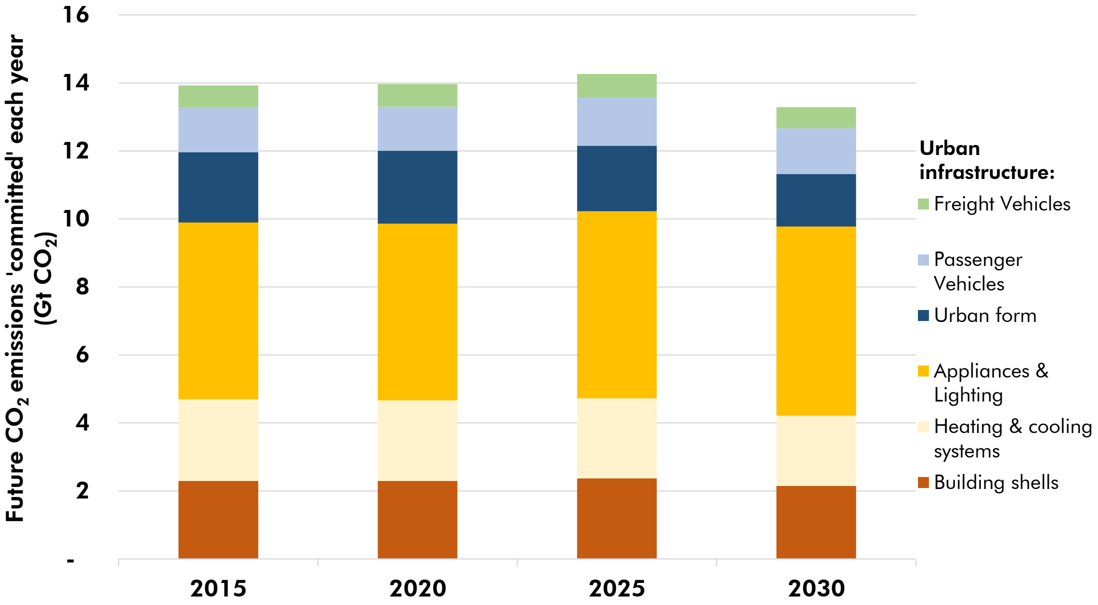
3. RESULTS

We find that the future emissions committed by new urban buildings and transport infrastructure would average about 14 Gt CO_2 annually over the next 15 years, assuming the recent plans and trends of the reference scenario. Nearly three-quarters of this is from new buildings and building equipment (including heating and cooling equipment, as well as appliances and lighting), and the remainder is from new transport infrastructure (vehicles and urban form). In total, urban development between 2015 and 2030 is on a path to commit more than 220 Gt of future CO_2 emissions.

Of the types of infrastructure displayed in Figure 2, urban jurisdictions have substantial policy influence over building shells, building heating and cooling systems, and urban form (Erickson et al. 2013). Local jurisdictions tend to have less direct influence over appliances and lighting, but may still, in some cases, be able to influence these through local energy codes. Likewise, local jurisdictions typically have less direct influence over the efficiency of passenger vehicles or the fuels they use, except in select cases where local licensing requirements or fuelling infrastructure (e.g. for electric vehicles) influences vehicle choice.

[4] As measured by passenger-kilometres by mode for passenger transport and tonne-kilometres for freight transport.

Figure 2: Future CO_2 emissions committed by new urban infrastructure in the reference scenario

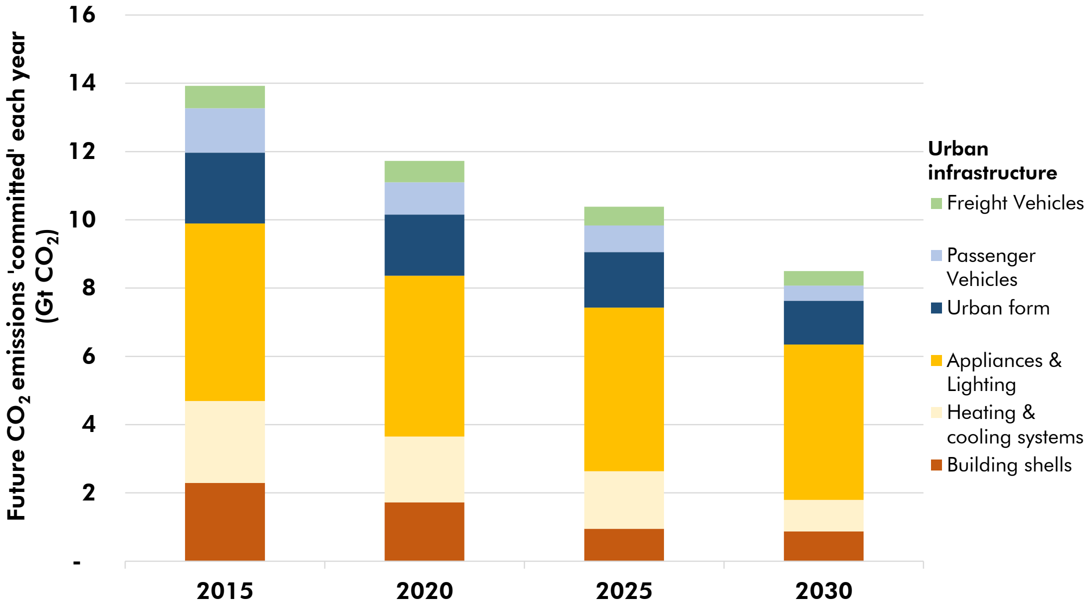


In the urban action scenario, new urban development takes on a more compact form, with less vehicle travel, a reduced demand for new vehicles, and substantially more efficient new buildings. In the urban action scenario, emissions commitments made annually decline from about 14 Gt CO_2 to 8.5 Gt CO_2 by 2030 (Figure 3), reflecting a rapid transition in standards, norms and practices for nearly all energy-consuming infrastructure and equipment, including new building shells, heating systems, appliances, lighting, and vehicles. Cumulatively, in the urban action scenario, urban development between 2015 and 2030 commits nearly 180 Gt CO_2, 20% less than in the reference scenario.[5] This represents a highly ambitious scenario for low-carbon urban development, and one that, in principle, is consistent with a global carbon budget of about 1,000 Gt CO_2.[6]

[5] Note, however, that in some cases a long-term transition to low-carbon urban areas may require temporary increases in emissions commitments – for example, if an urban area retired inefficient infrastructure early in order to replace it with more efficient infrastructure, such as a retiring an existing road corridor and replacing it with public transit. These types of effects are not captured in our analysis.

[6] We claim that the urban action scenario is consistent with a 1,000 Gt CO_2 carbon budget, given that the IEA's scenarios on which it is based were designed to be consistent with a similar budget, and the urban action scenario is even more ambitious.

Figure 3: Future CO_2 emissions committed by new urban infrastructure in the *urban action* scenario



In the sections that follow, we briefly discuss the results for the two primary types of infrastructure: buildings and transport systems. We then discuss how future CO_2 commitments by urban infrastructure contribute to the global carbon budget.

3.1 Urban buildings

In the reference scenario, investments in new buildings – and new equipment within existing buildings – represents the strong majority (>70%, or almost 10 Gt CO_2 annually) of future emissions committed in urban areas each year. More than half of this is due to numerous individual investments in building appliances and lighting, such as ovens and stoves, refrigerators, lighting, washing machines, and computers and electronics. Urban residents (and businesses) are purchasing this equipment at rapidly increasing rates, especially in developing countries. (Cities in non-OECD countries represent about 70% of the emissions commitments in 2030 for appliances and lighting). Even though the equipment are not always long-lasting (e.g. consumer electronics), the cumulative effect of these purchases is substantial, at least assuming current trends in regional power grids.

Building heating and cooling, including that locked in by inefficient building shells, represents the remaining 45% of annual CO_2 emissions commitments associated with buildings. Commitments due to heating and cooling equipment and building shells are more evenly split between cities in OECD and non-OECD countries, as many cities in OECD countries, though not growing as rapidly, have colder climates and correspondingly greater heating demands.

Substantial opportunities exist to reduce these emissions commitments, especially through energy codes that limit energy consumption. For example, in the urban action scenario, heating and cooling demand from new buildings and equipment are reduced by 20% compared with the reference case by 2020, and by more than 50% by 2030, leading to corresponding reductions in committed CO_2 emissions (Erickson and Tempest 2014).

We find that the aggressive actions taken in the urban action scenario could reduce cumulative CO_2 commitments associated with urban buildings by 30 Gt CO_2 by 2030, close to a year's worth of current global CO_2 emissions. (See Appendix B for detailed results for buildings.)[7]

3.2 Urban transport infrastructure

Investments in urban transport infrastructure – the roads to carry vehicles, plus the vehicles themselves – commit about 4 Gt, or more than 25%, of urban CO_2 commitments each year in the reference scenario. We attribute about half of this to expansion of urban form – as sprawling settlements and road networks continue to enable car-dominant lifestyles; this is on the order of 2 Gt CO_2 annually in the near term. The large majority (~80%) of these future CO_2 emissions commitments occur in cities in non-OECD countries, many of which are rapidly expanding into surrounding peri-urban and rural areas. We attribute the remainder, also about 2 Gt CO_2, to inefficient vehicle choices. Lock-in due to vehicle choice is more balanced between cities in OECD and non-OECD countries, since existing vehicle stocks in OECD countries are already high, and are continually being replaced.

Relatively few studies have explored the extent to which infill development, instead of sprawling development, could reduce community-wide vehicle travel demands and future CO_2 emissions commitments. The urban action scenario analysed here assumes that compact urban forms could reduce private passenger vehicle travel by 20% community-wide compared with the reference case in 2030, and that new passenger vehicles put in service in 2020 could be 15% more efficient and 40% more efficient in 2030 (Erickson and Tempest 2014). (Improvements in freight vehicles are assumed to be somewhat more modest.) Together, these improvements could reduce urban CO_2 commitments by nearly 15 Gt CO_2 cumulatively between now and 2030.[8]

3.3 Discussion: Urban carbon lock-in and the global carbon budget

In the near term, and assuming current and recently proposed policies, each year urban infrastructure will commit roughly 14 Gt CO_2 of future CO_2 emissions. Similarly, investments in other types of infrastructure – e.g. rural buildings, long-distance transport infrastructure, industrial facilities – also commit future CO_2. Based on information from the IEA, we estimate these other commitments at about 34 Gt CO_2 per year as of 2015 (IEA 2012). Altogether, this suggests that the infrastructure being put in place each year around the world will emit nearly 50 Gt CO_2 in the future.

These expected future commitments are additional to the expected emissions from infrastructure that is already in place. As the IEA and others have found, more than 800 Gt CO_2 are already committed by infrastructure built and equipment purchased before 2015 (including emissions between 2012 and 2015).[9] Adding nearly 50 Gt CO_2 per year of new commitments to an existing commitment of 800 Gt CO_2 suggests that total emissions commitments are likely to exceed the 1,000 Gt CO_2 budget before 2020. As shown in Figure 4, by 2030, without further policy action, the commitments could reach 1,500 Gt CO_2.

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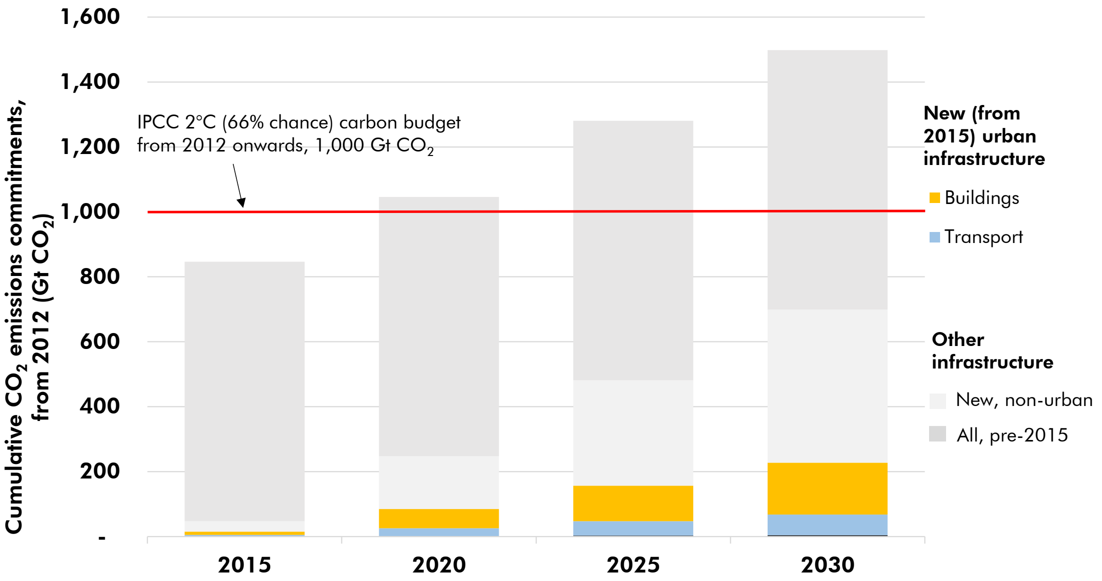
[7] Economic analysis of the urban action scenario has found that these actions in the building sector represent an economic opportunity (net cost savings, on an NPV basis) on the order of 170 billion USD annually (Gouldson et al. 2015).

[8] As with the building sector, investments in low-carbon urban transport infrastructure reduce later fuel expenditures to such a great extent that the net present value of such actions, even though capital-intensive, is 200 billion USD annually (Gouldson et al. 2015).

[9] Based on our analysis of estimated energy-related CO_2 emissions from locked-in infrastructure as of 2011 and projected to be in existence as of 2017, less those emissions attributed to power plant emissions associated with new urban demand, which we instead assign to future power-consuming infrastructure in urban areas (IEA 2012).

Figure 4: Cumulative CO_2 emissions committed from 2012 onwards by infrastructure in the reference scenario



Of this, our analysis suggests that approximately 45 Gt CO_2 of commitments can be avoided through actions pertaining to new infrastructure investments available at the urban level, chiefly through actions to set energy efficiency standards on building heating systems, shells, appliances, and lighting (30 Gt CO_2), passenger and freight vehicle standards (9 Gt CO_2), and compact urban form that reduces vehicle travel (5 Gt CO_2).

Of course, the path to limiting emissions to 1,000 Gt CO_2 and keeping warming within 2°C is not only about limiting future commitments, urban or non-urban. It is also crucial to unlock a substantial portion of the existing ~800 Gt CO_2 of emissions committed by existing infrastructure. In the urban context, this will especially involve retrofits of buildings to highly efficient levels (Erickson and Tempest 2014). Outside the urban environment, a critical component of unlocking carbon-intensive infrastructure will be to decommission coal-fired power plants and replace them with very low-carbon power (Hood 2014). To the extent that local governments have influence over their electricity systems, they can further assist with this transition: through public utilities, incentives for local and distributed renewable power, or, perhaps most importantly, by advocating for grid- and national-level change.

4. CONCLUSIONS

Current and future energy-consuming and -producing infrastructure will substantially determine the world's future CO_2 emissions. As the IEA and others have found, infrastructure that is already in place, if left in operation until the end of its average technical lifetime, has already "committed" about 800 Gt CO_2 of future emissions. This is a substantial portion of the world's remaining carbon "budget" of 1,000 Gt CO_2 (measured from 2012) needed to stay within a 2°C pathway. If current trends continue, new infrastructure construction could result in the entire carbon budget being committed before 2020.

This analysis has focused on the role of *urban* infrastructure in new CO_2 emissions commitments. Of the roughly 45 Gt CO_2 of new commitments expected annually over the next few years (Erickson et al. 2015a), we attribute about 14 Gt CO_2 (30%) to urban infrastructure. This indicates that new urban infrastructure will play a substantial role in setting future CO_2

emissions pathways. In particular, construction of new urban buildings and transport systems brings an important opportunity to avoid locking in inefficient pathways and, instead, deploy the most-efficient technologies and urban design. Over the next 15 years, our analysis indicates that by pursuing low-carbon urban infrastructure instead of current pathways, urban policy-makers could avoid committing about 45 Gt CO_2 of future emissions. Building very low-carbon infrastructure now will also help develop the institutions, such as skilled labour forces, that will be necessary to deploy even lower-carbon infrastructure in the future. The opportunity to avoid new lock-in is especially great in rapidly urbanizing areas in developing and emerging economies, particularly in South Asia and East Asia.

As others have shown, these actions would also, in the long term, yield substantial energy cost savings, on the order of 500 billion U.S. dollars per year (Gouldson et al. 2015). Furthermore, making these choices now, instead of attempting expensive retrofits later, can substantially lower the cost of meeting stringent climate objectives. For example, whereas the marginal cost (per tonne of CO_2 avoided) of meeting very stringent energy performance standards for new buildings is relatively small – less than 10 USD/t CO_2 – the cost of retrofitting buildings to that same standard later can be many times higher: 50 USD/t CO_2 or more (McKinsey & Company 2009).

For cities that are already highly built out, especially in developed regions such as North America and Europe, retrofitting, though more expensive, is more pertinent. It is also necessary, if urban areas are to play a substantial role in “unlocking” the existing roughly 800 Gt CO_2 of commitments. As addressed in prior work, one of the most critical needs is to retrofit existing urban buildings for substantially better energy performance.

Urban areas around the world have a substantial opportunity to avoid carbon lock-in and leave the door open for further “green growth” (Erickson et al. 2015b). As they further develop their cities, local leaders can implement policies for compact urban form, public and non-motorized transportation, and very low-energy buildings. These actions are necessary to reduce emissions, avoid higher-cost retrofits or redevelopments later, and decrease the cost (and increase the likelihood) of meeting stringent climate goals.

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APPENDIX A: METHODOLOGY DETAILS

As described in the main body, this report analyses the future CO_2 emissions commitments of infrastructure, with a focus on both new and already-existing infrastructure. This appendix provides further detail on the methods for each.

In commitment-based CO_2 emissions accounting (Davis et al. 2010; Guivarch and Hallegatte 2011; Davis and Socolow 2014), all anticipated future emissions from new capital deployed in a given year are counted in that year rather than in the years that actual emissions occur. (The committed emissions of a unit of capital investment are the integrated expected annual emissions over the lifetime of that investment). In the simplest form, committed emissions for any given investment can be expressed by the following equation:

$$Committed\ CO2_{Investment} = \sum_{i=1}^{\substack{Investment \\ Lifetime}} Fuel\ use_{year\ i} \times\ Fuel\ carbon\ content_{year\ i}$$

As an example, the committed emissions from a vehicle purchase would be calculated as the expected lifetime of the vehicle multiplied by the fuel (e.g., gasoline, diesel) use in each year by the carbon content of the fuel used in each year. Here we describe the assumptions used for all committed CO_2 calculations, by sector and type of infrastructure or equipment.

Note that we focus only on energy *use* by the infrastructure because this is typically much greater than the energy used to construct the infrastructure and its component parts and materials, such as cement or steel (Sartori and Hestnes 2007). More fundamentally, future energy-related emissions are more congruent with the concept of "lock-in", which concerns how current decisions, such as the energy performance of a building, constrain future pathways, such as the long-term energy and emissions use of that building.

Transport

For new urban transport infrastructure, we estimate CO_2 commitments for both passenger transport (private, buses, and trains) and freight transport (urban trucking). For each, we assign emissions to one of two activities: expansion of urban form, or purchase of new vehicles, under the notion that these activities share responsibility for future emissions from transportation of people and goods.

Estimates of future new vehicle purchases or expansion of urban form are not readily available, but the IEA does report its assumptions about future vehicle *travel*. Therefore, instead of basing our calculation of committed CO_2 on estimates of infrastructure investment (as in the equation above), we instead make the simplifying assumption that travel per vehicle is constant, and that increases in vehicle travel are a reasonable proxy for infrastructure investment.

We then develop a procedure to these estimates of future vehicle travel to apportion responsibility to changes in urban form (Figure 5, blue areas of chart) and vehicle purchase choice (Figure 5, beige area).

As the lifetime of urban form (estimated here conservatively at 50 years) is substantially longer than the lifetime of a new vehicle purchase, the decision to construct a new road, or replace one that would otherwise be retired or repurposed, commits continued travel demand over a longer period of time. This is why the last urban form emissions (blue wedges) continue even after the last emissions associated with a simultaneous vehicle purchase are released (beige wedge).

Figure 5: How passenger travel (and corresponding CO_2 emissions) is assigned to roads and urban form (blue shading, both light and dark) or to vehicle choice (beige)

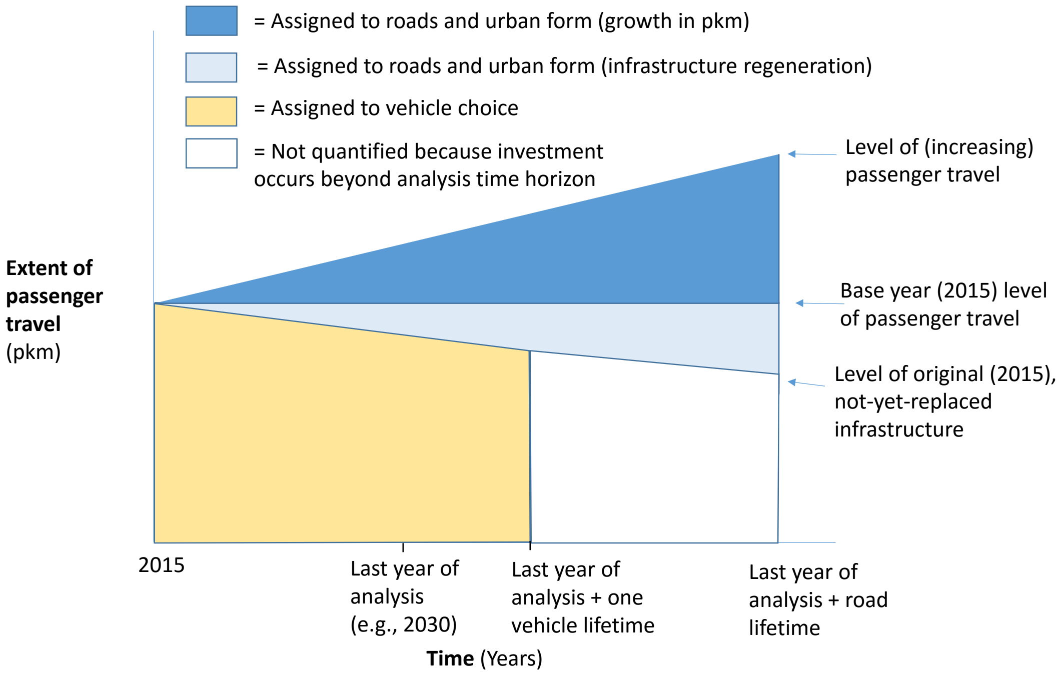


Table 2 describes in more detail the logic for quantifying and attributing the committed emissions for new urban transportation infrastructure. Urban form is assigned all emissions related to lifetime vehicle travel on new and "refreshed" urban form, up to the level of the lowest-carbon options widely available. (We assume a natural replacement and maintenance interval for urban form of 50 years, and hence one-50th of the travel activity each year occurs on newly "refreshed" urban infrastructure.) Emissions are assigned only at the level of the lowest-carbon option, under the assumption that urban form does not predetermine the vehicles and modes that travel within that form, i.e. on its roads. Any remaining emissions (in excess of lowest-carbon available vehicle option) from vehicle travel on new and refreshed urban form is assigned to vehicle choice in the year in which the vehicle was purchased. In addition, vehicle choice is also attributed all committed emissions from vehicle purchases with travel activity equivalent to that on urban form on pre-existing (as of 2015) and never-refreshed infrastructure.

Table 2: Calculation logic for attributing committed CO_2 to urban form vs. vehicle choice for any given year t

Step in calculation logic	To urban form	To vehicle choice	
		For expanded / refreshed urban form	For pre-existing (as of 2015) urban form
Activity (Δpassenger-kms, pkms, or Δtonne-kms, tkms)	Annual increase in activity plus annual activity on urban form refreshed in that year	Increase in activity relative to 2015 plus annual activity on urban form refreshed since 2015 x replacement rate (1/ average vehicle lifetime)	Activity associated with pre-existing 2015 urban form (that remains in operation) x vehicle replacement rate (1/average vehicle lifetime)[10]
Fuel intensity (GJ/pkm)	At lowest-carbon vehicle options (widely available) over urban form lifetime	At excess (average new vehicle minus lowest-carbon option)	At average new vehicle purchase
Carbon content of fuel (tCO_2/GJ)	At lowest-carbon vehicle options (widely available) over urban form lifetime	At average new vehicle purchase	At average new vehicle purchase.
Lifetime (years)	Assumed lifetime of urban form (50 years)	Vehicle lifetime (18 years)	Vehicle lifetime (18 years)
Committed CO_2 in year t	Product of all above		

Buildings

We estimate CO_2 commitments associated with infrastructure and equipment for building heating and cooling, appliances and lighting. This is done for both new buildings and previously constructed buildings requiring equipment upgrades or replacements.

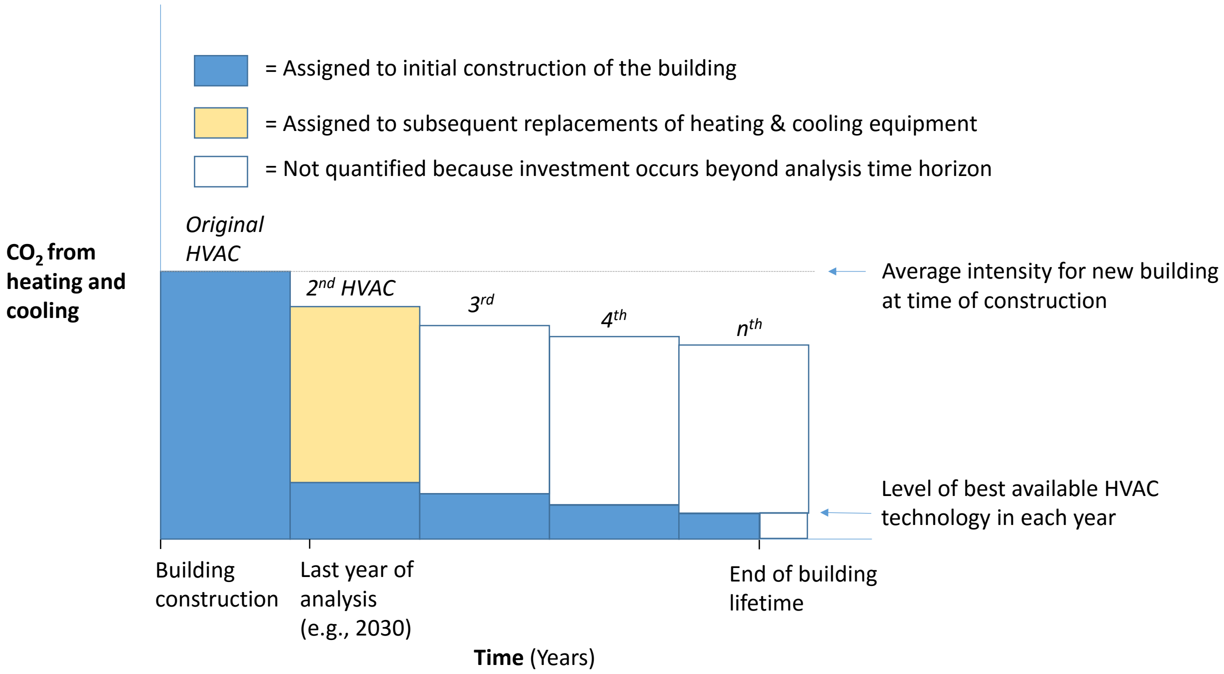
Space heating and cooling

For heating and cooling, we treat a new building as a package at the time of construction. We assign commitment emissions to the building "shell" based on its HVAC initial components and their expected lifetime. We do so because, with some exceptions, decisions on, and investments in, heating/cooling and other equipment are generally made as part of building design and construction, and the efficiency of the building shell substantially determines the choice and energy use of later HVAC systems. However, most equipment does not last as long (e.g. 10–30 years) as the building shell (often 50–100 years), and therefore building owners or managers must make replacement decisions; we attribute the emissions committed by those decisions to subsequent replacement of heating and cooling equipment. (All water heating equipment is also assigned to this latter category (equipment purchase), on the assumption that it is not as limited by building shell design.)

[10] The majority of these emissions are attributed to existing urban form, but not all, since some percentage of future miles travelled will be associated with new or replacement roads. For private vehicles, the share of pkms is ~80% (based on a 50-year road lifetime and 18 (+/- 4) year vehicle life). For shorter-lived equipment, the share is higher (e.g. for 9-year lifetime buses, ~90%) and for longer-lived equipment, the share is lower. The remainder is captured in the expanded and refreshed vehicle choice category, and is excluded here to avoid double-counting of vehicle choice emissions.

This process is illustrated, for an individual building, in Figure 6, where each block represents a new heating, ventilation and/or air conditioning (HVAC) system; equipment is assumed to be replaced, on average, every 18 (commercial) or 19 years (residential).[11]

Figure 6. How CO_2 emissions from HVAC equipment are assigned to the year of initial construction (blue) and to the years of subsequent replacement of equipment (beige)



[11] We apply a probabilistic distribution of equipment replacements based on a normal distribution around the mean equipment lifetime. For residential space conditioning the average lifetime used is 19 ± 10 years, and for commercial it spaces is 18 ± 5 years (IEA 2012). Therefore, a minor share of equipment needs to be replaced within the first 5–10 years (~20% for residential, 10% for commercial) rather than all equipment of a certain installation year (vintage) needing replacement *en masse* in a single future year.

Table 2 describes the calculation logic and attribution for committed emissions from building space heating and cooling, following the general form of Equation 1 above. New installation energy demand is derived from a combination of IEA projections and our previous analysis (Erickson and Tempest 2014), onto which we apply retirement rates (based on average equipment lifetimes) to determine the share (and annual rate of change) in new and pre-existing infrastructure energy demand.

Table 2: Calculation logic for attributing committed emissions for building HVAC systems

Step in calculation logic	**To building shell**		**To space heating & cooling system** (subsequent systems only)
	(first HVAC system)	(subsequent HVAC system)	
Heating & cooling demand (ΔGJ_{in} / year)[12]	Net growth in heating demand plus estimated building replacement from prior years' "new builds"	From equipment replacement in prior years' "new builds"	From equipment replacement in prior years "new builds"
Heating & cooling efficiency adjustment	None (1.0)	At ratio of scenario average to most efficient new heating/cooling technologies	1 minus the ratio of scenario average to most efficient new HVAC technologies
Fuel carbon intensity (Gt CO_2e / GJ_{in})	At scenario average new equipment carbon intensity	At carbon intensity of lowest-carbon technologies widely available (over building lifetime)	At scenario average new equipment carbon intensity
Lifetime of infrastructure	Average lifetime of heating & cooling system (19 years)	Average lifetime of HVAC system (19 years), subsequent systems through end of building life (80 years)	Average lifetime of HVAC system (19 years), subsequent systems installed before 2030
Committed emissions in given year (Gt CO_2)	Product of above		

For HVAC systems in buildings already in existence in the base year (here, 2015), we apply the method as described above. For example, new HVAC equipment investments in 2020 within a building constructed prior to 2015 only "commit" emissions to the extent that their heating systems exceed the best (i.e. lowest-carbon) heating system readily available at the time. Emissions attributed to the building shell are assigned to the year of construction, at some time prior to 2015, and at the level of the best (lowest-carbon) heating system readily available at the time.[13]

Other building equipment

For all other equipment (non-HVAC), the correlations between equipment and building design and construction are significantly weaker. It is likelier and more straightforward for the owner, rather than the builder, to determine the initial appliance or replace an appliance as opposed to a full HVAC system. In addition, appliance usage is not largely determined by building shell characteristics. Therefore, for non-HVAC equipment (including water heating, electronics, cooking, and miscellaneous other), all emissions commitments from fuel use and power consumption are attributed solely to the equipment (and none to the building shell). The calculation logic is described in Table 4.[14]

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[12] Some level of retrofits (0.5% per year in the reference scenario, 1.1% per year in the urban action scenario) improving the energy efficiency from previous builds is assumed when calculating replacement energy demand.

[13] The emissions for building shells constructed prior to 2015 are included as pre-existing emissions commitments, and are additional to the committed emissions estimates of the *World Energy Outlook*, which only describe the fuel-consuming equipment in use at that time. We estimate these commitments to be approximately 20 Gt CO_2.

[14] Water heating and space heating and cooling are included under the "Heating & Cooling Systems" category of Figures 2 and 3. All others are under the category "Appliances & Lighting".

Table 4: Calculation logic for attributing committed emissions for building appliances

Step in calculation logic	To all appliance purchases, all lighting purchases, all water heating purchases, and heating/cooling systems in house built prior to 2015
HVAC replacement energy demand (∆MWh or ∆GJ / year)	Net growth plus estimated equipment replacement from prior years
Emissions intensity (Gt CO_2e / MWh or GJ)	At scenario average new appliance energy intensity and fuel choice (including CO_2-intensity of electricity)
Lifetime of infrastructure (years)	At average lifetime (equipment-specific, ranges from 5 years for fluorescent lighting to 20 years for commercial appliances and equipment)
Committed emissions in a given year (Gt CO_2)	Product of above

While we attribute the indirect emissions associated with urban building equipment power consumption to either the equipment itself or the building shell, as described in the tables above, some of these future emissions are linked to power generation at pre-existing power plants. The estimate of pre-existing emissions commitments derived from IEA's *World Energy Outlook 2012*[4] already attributes these emissions to power plants at the point of fuel combustion. To avoid "double-counting" of these emissions, we subtract a share of the future electricity demand related emissions in urban buildings from the IEA's estimate of pre-existing commitments. Our analysis indicates that around 40% of power-related fossil fuel emissions through 2050 globally will come from power plants built prior to 2015. This share of building end use-related emissions amounts to approximately 80 Gt CO_2 through 2050, which we subtract from our initial estimate of pre-existing emissions commitments.

APPENDIX B: ADDITIONAL RESULTS

Buildings

Table 5: Annual emissions commitments (Gt CO_2) from new infrastructure installations in urban residential and commercial buildings, 2015–2030

Sector	Infrastructure or piece of equipment	2015	2020		2025		2030	
	Scenario	*Ref.*	*Ref.*	*U.A.*	*Ref.*	*U.A.*	*Ref.*	*U.A.*
Buildings, residential	Building shell	1.6	1.6	1.3	1.7	0.8	1.5	0.7
	Heating & cooling systems	1.6	1.6	1.3	1.7	1.2	1.5	0.7
	Appliances & lighting	2.8	2.9	2.6	3.2	2.8	3.1	2.5
	Subtotal	6.0	6.1	5.2	6.5	4.7	6.1	3.9
Buildings, commercial	Building shell	0.7	0.7	0.4	0.7	0.2	0.6	0.1
	Heating & cooling systems	0.8	0.7	0.7	0.7	0.5	0.6	0.2
	Appliances & lighting	2.4	2.3	2.1	2.3	2.0	2.5	2.1
	Subtotal	3.9	3.8	3.2	3.7	2.7	3.7	2.4
All buildings	**TOTAL**	**9.9**	**9.9**	**8.4**	**10.2**	**7.4**	**9.8**	**6.3**

Table 6: Cumulative emissions commitments (Gt CO_2) from new infrastructure installations in urban residential and commercial buildings, 2015-2030

Sector	Infrastructure or piece of equipment	2015	2020		2025		2030	
	Scenario	Ref.	Ref.	U.A.	Ref.	U.A.	Ref.	U.A.
Buildings, residential	Building shell	2	9	9	17	14	26	18
	Heating & cooling systems	2	10	9	18	15	26	19
	Appliances & lighting	3	17	17	32	30	48	43
	Subtotal	6	36	34	68	59	99	80
Buildings, commercial	Building shell	1	4	4	8	5	11	6
	Heating & cooling systems	1	5	4	8	7	11	9
	Appliances & lighting	2	14	13	25	24	37	34
	Subtotal	4	23	21	42	36	60	49
All buildings	**TOTAL**	**10**	**59**	**56**	**109**	**95**	**160**	**129**

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